Evaluating Swiftpoint as a Mobile Device for Direct Manipulation Input

A thesis
submitted in partial fulfilment
of the requirements for the Degree
of
Master of Science in Computer Science
in the
University of Canterbury
by
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Examining Committee

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University of Canterbury
2006

To my family for their endless love and support.

Abstract

Swiftpoint is a promising new computer pointing device that is designed primarily for mobile computer users in constrained space. Swiftpoint has many advantages over current pointing devices: it is small, ergonomic, has a digital ink mode, and can be used over a flat keyboard.

This thesis aids the development of Swiftpoint by formally evaluating it against two of the most common pointing devices with today's mobile computers: the touchpad, and mouse. Two laws commonly used with pointing devices evaluations, Fitts' Law and the Steering Law, were used to evaluate Swiftpoint. Results showed that Swiftpoint was faster and more accurate than the touchpad. The performance of the mouse was however, superior to both the touchpad and Swiftpoint. Experimental results were reflected in participants' choice for the mouse as their preferred pointing device. However, some participants indicated that their choice was based on their familiarity with the mouse. None of the participants chose the touchpad as their preferred device.

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Acknowledgments

I would like to thank Andy Cockburn and Richard Green for their advice, support, and guidance for the past two years. I would also like to thank Grant Odgers for funding, and supplying the equipment needed for the experiments.

Special thanks goes to Sofia Crosley, for teaching me so many things in life. Many thanks to Jason Alexander, Oliver Batchelor, Jay Holland, and Michael JasonSmith for their friendship, help, and proof reading. Last but not least my friends, Sung Bae, Nilufar Baghaei, Ehsanul Bashar, Mirko Eickoff, Oliver Hunt, Ryan Mallon, Nancy Milik, Pramudi Suraweera, Natashka, Anna Wingkvist, and Konstantin Zakharov, for the interesting conversations we had, and for their support and encouragement.

Chapter I

Introduction

In this thesis I present the evaluation of a new pointing device, called Swiftpoint. Swiftpoint was developed by a local Christchurch company, Simtrix, specifically for mobile computer users in constrained space. It is expected that Swiftpoint's small size, ergonomic design, and its elimination of transition time[1] will enable it to outperform some of today's the most common pointing devices with mobile computers.

I present the results of two experimental evaluations conducted to determine Switpoint's usability. The experiments employed two laws: Fitts' Law and the Steering Law. These two laws predict movement time, and compute the speed and accuracy of each device, for subsequent comparison with other pointing devices. Results of the experiments showed the superiority of Swiftpoint to one of the most common devices in today's mobile computers, the touchpad.

1.1 Early Computer Systems

Today computers can be seen everywhere, from airline reservations to gaming. They are a part of everyday life in the developed world, and increasing the performance of computer users would be of a great benefit to society. Hence computer usability researchers around the world strive to improve users' comfort and performance with graphical user interfaces (GUI), and the use of computers in general.

The Abacus and the Antikythera are among the earliest ancestors to computers. The Memex however, was one of the earliest prototypes of todays' computers that envisioned users interacting with a GUI. In the 1930s

[1] Transition time is the time a user takes to switch his or her hands between the keyboard and the pointing device.

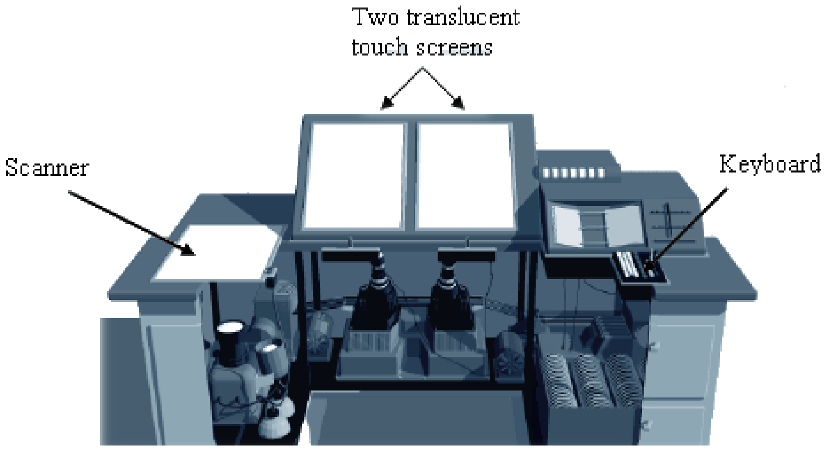


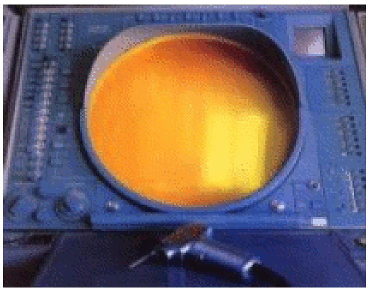
Figure 1.1: The Memex desk with two translucent screens on top (Dynamic Diagrams 2005).

Vannevar Bush envisioned a system *(Memex)* that is shaped as a desk with two translucent screens (to project material for reading), a scanner, and a keyboard (Figure 1.1), which would allow users to store and rapidly access books and microfilm records (Bush 1945).

The Semi Automatic Ground Environment (SAGE): a system for air defence radar processing, was the first system with a windowing interface. SAGE operators would use a light gun (Figure 1.2) to select targets on the console, and choose the best method to intercept these targets (Online Air Defence Museum 2000).

Another pioneering system to use a GUI was the Sketchpad (Figure 1.3), invented by Sutherland (1964) as part of his PhD thesis in 1963. Sketchpad enabled users to draw objects, such as electric circuits, mechanical, and animated drawings, by using a light pen on the computer display. Users can draw, copy, resize, move, erase, and modify drawings by pointing to the drawing with the light pen and pressing a button to select one of the displayed options (Sutherland 1964). Sutherland argues that Sketchpad changed the way people interact with the computer, by enabling the user to use a pointing device to interact with the graphical user interface.

Today's most popular pointing device is the computer mouse. The first



(a) The Semi Automatic Ground Environment (SAGE) radar processing system.

(b) SAGE operator using a light gun.

Figure 1.2: The Semi-Automatic Ground Environment SAGE radar system (Online Air Defence Museum 2000).

Figure 1.3: The Sketchpad (Mischitz 2001).

mouse (Figure 2.1) was invented by Douglas Engelbart in the early 1960s at the Stanford Research Institute (SRI). In 1968 Engelbart created the oN-line System (NLS) (Figure 1.4). The NLS was the first computer system that had a GUI with multiple windows, which enabled users to select hypertext links using a mouse (Reimer 1998, Tuck 2001).

Since the invention of the Sketchpad, computer users have been increasingly using GUIs in their interaction with computers. Today, after 43 years, GUIs have become a standard method of interacting with computers.

(a) The oN-line System with a display, keyboard, mouse, and a five chording-keyboard as a replacement for the keyboard.

(b) A close up view of the NLS controls.

Figure 1.4: The oN-line System (NLS) (Mischitz 2001).

1.2 *Pointing Devices*

To interact with a GUI, one needs a pointing device, such as mouse, touchpad, trackball, and touchpad. These pointing devices allow the user to point and click on objects such as buttons, scroll bars, and menus, which are commonly available in graphical user interfaces.

A wide array of computers — such as the personal computer (PC), laptop, tablet PC, personal digital assistant (PDA) — are available in the market. Some computer users use the preinstalled pointing device, such as the isometric joystick and touchpad in laptops, and stylus with tablet PCs. Other users prefer to use their own pointing device, such as a mouse or a trackball, depending on the level of comfort and efficiency the user perceives. A brief overview of these pointing devices is given below.

- Mouse (Figure 2.5): Is a device with a number of buttons, and a ball or optical sensor that translates mouse movement to cursor movement.

- Trackball (Figure 2.6(b)): Is a device that resembles an inverted mouse, where the user controls the ball through his or her finger tips.

- Stylus and tablet (Figure 2.7): Is a pen like device that uses a tablet to map its movement to on-screen cursor movement.

- Touchpad (Figure 2.8): Is a rectangular touch sensor, that translates users' finger movement into on-screen cursor movement. Touchpads can be seen today embedded in laptops.

- Isometric Joystick (Figure 2.9): Is a small rubber stick, located between the 'G', 'H', and 'B' keys, on the laptop QWERTY keyboard. Distance covered by the cursor depends on the force applied, by the users' finger, on the isometric joystick.

Pointing devices are divided into two categories: (a) direct mapping, such as light pen, where the user is capable of making an input at the exact location where information is presented; and (b) indirect mapping, such as mouse, trackball, touchpad, stylus, and isometric joystick, where the input and presentation mediums are distinct. More accuracy, cognitive processing, and an increased hand-eye coordination is required with indirect mapping (Zuhlke & Krauss 1999).

The mouse is currently the most widely used pointing device (Zhai 2004*b*). There have been many variations of the mouse since its invention in 1963, however, most if not all of the current pointing devices are either not as efficient as the mouse or, in the case of a mobile user (for example, laptop user in a train or plane), require space to operate. Even though the mouse has prevailed in almost all studies that compared pointing devices, such as (Card et al. 1978, Douglas & Mithal 1994, MacKenzie 1991, Accot & Zhai 1997, MacKenzie et al. 2001, Oh & Stuerzlinger 2002), there are many shortcomings with the mouse, such as the following.

- Not practical in constrained spaces, since users would resort to placing the mouse on a small flat surface, which would restrict mouse movement and their ability to perform fine tasks.

- Hard to use for writing or drawing, because of the way the mouse is held and its large contact area with the surface, is different from the more natural way of holding the pen with its fine nib point.

- Constant hand movement between mouse and keyboard, when editing a document, for example.

- Forces the user to position his or her hands beside the keyboard rather than, the more natural position, in front of the users' body (Figure 3.4) (Simtrix 2004).

- Requires cables to connect to the computer, or charging in case of a wireless mouse.

- Requires storage space when traveling.

To overcome such limitations, a new pointing device, called Swiftpoint, was invented by Simtrix, a company based in Christchurch, New Zealand. Swiftpoint is a small wireless pointing device that can be used on top of a keyboard. It is designed mainly for mobile users, and is expected to outperform current pointing devices such as pen, touchpad, and mouse, in terms of efficiency, speed, accuracy, and user preference.

1.3 Overview of Evaluation Methods

Two laws are commonly used to test, compare, and determine the usability of new pointing devices: Fitts' Law and Steering Law. These two laws predict movement time, and compute the speed and accuracy of each device, for subsequent comparison with other pointing devices. Section 2.2 describes these laws in more detail.

1.3.1 Fitts' Law

Fitts' Law (Fitts 1954) predicts participants' movement time in target acquisition tasks. It states that the movement time (MT) to acquire a target depends on the distance (D) to the target and width (W) of the target (Card et al. 1978, MacKenzie 1991, MacKenzie & Soukoreff 2003, Soukoreff & MacKenzie 2004, Zhai, Kong & Ren 2004), and is described by the following relationship,

$$MT = a + b \times \log_2 \left(\frac{D}{W} + 1 \right) \tag{1.1}$$

The values, a and b are constants, and the logarithmic function represents the index of difficulty (ID) of the task (Equation 2.3).

1.3.2 Steering Law

The Steering Law (Accot & Zhai 1997, 1999) predicts the time users take to steer through a constrained tunnel, such as nested menus. The Steering Law could be expressed as

$$T_c = a + b \int_C \frac{ds}{W_s} \tag{1.2}$$

where, T_c represents the average time spent to steer through tunnel c, a and b are constants, while the integral function represents the index of difficulty (ID) of the task (Equation 2.27).

1.4 Experimental Overview and Hypotheses

It is hypothesised that Swiftpoint will outperform both the mouse and touchpad in terms of speed, accuracy, efficiency, and subjective preference; in particular,

1. Users would select targets faster with a lower error rate using Swiftpoint;

2. Users would spend less time to steer through tunnels with Swiftpoint;

3. User would indicate their preference for Swiftpoint, in terms of speed, accuracy, and comfort, in a NASA-TLX questionnaire.

These hypotheses will be evaluated using three standard evaluation methodologies:

- Fitts' Law and ISO 9241-9 standard[2] modeling of target acquisition, to compare the performance of different pointing devices in discrete pointing tasks.

[2] Subsection 2.2.2 discusses the ISO standard in more detail.

- Steering Law modeling of continuous dragging tasks, to compare the performance of different pointing devices.

- NASA Task Load Index (NASA-TLX) (Hart & Staveland 1988) measures of subjective satisfaction and workload, to rate measures like effort, frustration, and mental demand.

Two experiments will be conducted to test the speed and accuracy of Swiftpoint against two other pointing devices, Microsoft IntelliMouse, and Cirque Smart Cat touchpad. The first experiment (Chapter 4) will be based on target acquisition tasks (i.e., will use Fitts' Law to compare pointing devices). Participants will be presented with an interface that resembles Figure 2.11, and will be asked to select sequentially highlighted targets as fast and accurately as possible, as recommended by ISO 9241-9 standard.

The second experiment (Chapter 5) will be based on trajectory–based tasks (i.e., will use the Steering Law to compare pointing devices), participants will be asked to drag the cursor through a number of highlighted tunnels, as fast and accurately as possible.

A NASA-TLX based questionnaire will be used to evaluate the subjective satisfaction of Swiftpoint. After completing the two experiments, participants will be asked to rank each pointing device in terms of accuracy, speed, preference, finger, wrist, arm fatigue, and general comfort. Another NASA-TLX based questionnaire will be used to rate the performance, effort and frustration as well as mental, physical, and temporal demands of Swiftpoint.

1.5 Thesis Overview

A brief history of pointing devices, and a detailed discussion of the evaluation methods used to test and compare Swiftpoint to the touchpad, and the mouse, is presented in Chapter 2. Chapter 3 gives a detailed description of Swiftpoint, its key features, advantages, ergonomics, and future. I then present the results of two experimental evaluations conducted to determine Switpoint's usability in Chapters 4 and 5. This is followed by results of the subjective preference questionnaires in Chapter 6. Finally future work and conclusions are presented in Chapter 7.

Chapter II

Related Work

This chapter will focus on the development of pointing devices, and the evaluation methods used to test these devices. The history of the mouse, and the wide array of pointing devices invented since Doug Engelbart invented the mouse in the early 1960s, is discussed in section 2.1. We then discuss the development of evaluation techniques, in particular Fitts' Law and the Steering Law, used to test pointing devices in section 2.2.

2.1 History of Pointing Devices

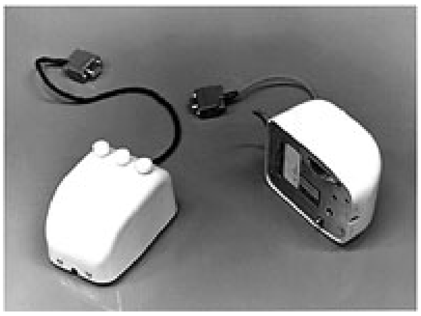
The 1960s and 1970s witnessed the invention and early development of the mouse we see today. The mouse was first envisioned by Douglas Engelbart in the early 1960s. With the help of Bill English, the chief engineer at the Stanford Research Institute (SRI), the first mouse was manufactured in 1964 (Stanford Research Institute SRI 2000). The mouse (Figure 2.1(a), and 2.1(b)) was carved out of wood, had one button, and two perpendicular metal wheels to capture the X-Y coordinates of the mouse as it moves; these coordinates were then translated into on-screen pointer movement. In 1967 Engelbart developed another model of the mouse with three buttons (Figure 2.1(c)), and demonstrated it publicly with the NLS system in 1968. A patent was issued for the later model in 1970 (Engelbart 1970).

Bill English joined Xerox PARC in the early 1970s, to create another version of the mouse. The new mouse (Figure 2.2), called the Alto I mouse[1], was smaller than the NLS mouse, had three buttons, a steel ball instead of two metal wheels, and two smaller perpendicular ball bearings that detected the motion of the ball.

[1] The Alto I mouse was named after the Alto I computer developed by Xerox PARC in 1973.

(a) The first computer mouse with one button.

(b) The first mouse with two perpendicular wheels.



(c) The second model of the mouse with three buttons.

Figure 2.1: The first mouse (Old Mouse 2001, Wikimedia Foundation 2006).

Figure 2.2: The Alto I mouse with three buttons (Old Mouse 2001).

(a) The Xerox 8010 Star mouse with two buttons, and a DB9 pins connector.

(b) The bottom of the Xerox 8010 Star mouse showing the LED sensor.

Figure 2.3: The Xerox 8010 Star mouse (Old Mouse 2001).

The earliest optical mice were invented in the early 1980s, by Steve Kirsch at the Mouse Systems Corporation, and Richard Lyon at Xerox. The optical mouse did not any use metal wheels or a steel ball, instead it used an optical sensor and a light emitting diode (LED) to detect the movement of the mouse. Kirsch's mouse had an optical sensor with four quadrant infrared detectors, and a special metallic checkerboard mouse pad with an embedded X-Y coordinate system to detect mouse movement relative to the pad. Richard Lyon, on the other hand, invented the Xerox 8010 Star mouse[2] (Figure 2.3) with two buttons, DB9 pins connector, and an embedded chip that detected its X-Y coordinate movement, on a sheet of printed dot pattern[3], relative to the mouse.

As major companies competed to manufacture the optimal mouse, Apple opted to use the mechanical mouse with a rubber ball, and one button[4] (Figure 2.4), with its Apple Lisa Computer in 1983.

As computers gained more popularity, and as computer power, storage, and graphics processing speed increased, user needs and expectations of the

[2] The Xerox 8010 Star mouse was named after the Xerox 8010 Star computer system, invented in 1981 at Xerox labs.

[3] The Xerox 8010 Star mouse worked on any surface that had a distinct texture (Old Mouse 2001).

[4] Apple used a one button mouse to make button selection easier and less confusing for novice users (Perry & Voelcker 1989).

(a) The Apple Lisa mouse with one button.

(b) The bottom of the Apple Lisa mouse with the rubber ball.

Figure 2.4: The Apple Lisa mouse (Old Mouse 2001).

Figure 2.5: A wireless Logitech laser mouse with a scroll wheel, and multiple buttons (Logitech 2006).

mouse increased. To satisfy users' needs, the mouse was modified over the years to have a more ergonomic shape, a scroll wheel, a number of buttons, wireless, optical, and now laser technology for more precise movement tracking (Figure 2.5).

While the development of the mouse was underway, alternative pointing devices such as the trackball, pen, isometric joystick, and touchpad were being developed. The first trackball was manufactured in 1966 by Orbit Instrument Corporation for the military and air traffic control systems (Figure 2.6(a)) (Old Mouse 2001). Today, the computer trackball has the shape of an inverted mouse (Figure 2.6(b)), in which the user moves the ball with his or her fingers and the on-screen cursor moves accordingly. The trackball has been modified over the years to include a number of buttons, wireless,

(a) The first trackball manufactured for air traffic control systems.

(b) An optical Logitech trackball with multiple buttons.

Figure 2.6: The first trackball, and one of the latest trackballs from Logitech (Logitech 2006, Old Mouse 2001).

and optical sensors.

A pen or stylus is used with devices such as Wacom tablets, tablet PCs, and personal digital assistants (Figure 2.7). The stylus was first used with the Grafacon tablet in 1964, as an alternative and a more accurate pointing device for precision tasks, such as drawing and two–dimensional computer graphics. There has been a wide variety of tablets manufactured since 1964, most of which however, use the same technology to detect the position of the stylus. Modern tablets have a grid of horizontal and vertical wires, lying underneath the surface. Whenever the stylus meets the surface, the underlying horizontal and vertical wires touch causing an electric current at that particular location, thus producing a unique X-Y coordinate location. Major tablet designers, such as Wacom, use electromagnetic induction to communicate with the stylus. With induction, the tablet acts as a transmitter and receiver (i.e., the tablet sends the X-Y coordinate to the pen, and also receives signals from the pen, such as button click, or a change in pressure exerted on the stylus).

The touchpad, and the isometric joystick (Figures 2.8, and 2.9) were designed to be used with laptop computers. The isometric joystick, originally called the trackPoint, was designed at IBM by Ted Selker as a mouse replacement. It is a small rubber stick, found on the keyboard between the 'G', 'H', and 'B' keys. The isometric joystick operates by measuring the pressure

Figure 2.7: A Wacom tablet with a stylus on top (Wacom 2006).

Figure 2.8: A laptop with a touchpad.

Figure 2.9: The isometric joystick (Laptop Worldwide 2006).

exerted on the joystick, and according to which, the on-screen pointer moves at a speed proportional to the pressure. Touchpads are embedded today with every laptop computer, although separate touchpads could also be used with desktop computers. Touchpads have capacitors that sense finger movement, and according to to the pressure and speed of the finger, the on-screen pointer is moved.

2.2 Evaluation Techniques

Every user interface designer aims to design the perfect interface or device, one that is: easy to learn and memorize, reliable, efficient, and satisfies the user. The perfect interface does not exist. However, human computer interaction researchers, through usability evaluations, strive to make the best usable interface, one that is preferred by most participants. Usability evaluations would help interface designers to identify any problems with the interface or device in the early stages of the design, by achieving the following:

- Examine if the interface or device meets the user requirements.
- Gather users' opinions about the interface or device, on matters such as ease of use, and learnability.
- Identify any problems with the design of the interface or device.

There exist many techniques for evaluation, such as surveys, empirical, and observational techniques. But for the purpose of evaluating Swiftpoint, only the first two evaluation techniques will be used. The empirical technique is considered as one of the most powerful evaluation methods, which examines an interface or device by conducting usability experiments to test the proposed hypotheses (Dix et al. 1998). To evaluate Swiftpoint, two laws will be used to conduct two evaluation experiments: Fitts' Law and the Steering Law. These laws along with subsequent NASA-TLX questionnaires, help researchers to identify important variables about the pointing devices being examined, such as speed, accuracy, error rate, learn ability, and subjective satisfaction. Subsections 2.2.1 and 2.2.3 respectively describe these two laws in more detail, while subsection 2.2.2 introduces modifications to Fitts' Law.

2.2.1 Fitts' Law

Fitts' Law is a psychological model that describes human movement, during rapid aimed selection tasks. Fitts' mathematical model (Equation 2.3) (Fitts 1954) was based on earlier research by Shannon & Weaver (1949) on the theory of communication. One of Shannon and Weaver's theories, theorem 17, inspired Fitts to investigate the information capacity of the human motor system. The theorem states that

> The capacity of a channel of band W perturbed by white thermal noise of power N when the average transmitter power is limited to P is given by
>
> $$C = W \log_2 \frac{P+N}{N} \tag{2.1}$$

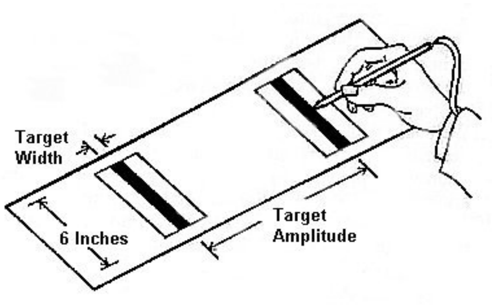


Figure 2.10: Fitts' reciprocal tapping experiment (Fitts 1954).

where, through encoding, the information capacity C measured in bits per second, could be transmitted with arbitrarily small frequency of errors (Shannon & Weaver 1949).

Fitts wanted to unify previous research on the human motor capacity into one law that correlates the amplitude, duration, and variability of movement (Fitts 1954). To achieve such unity, Fitts conducted three experiments, in which he varied the amplitude and variability of movement.

1. A reciprocal tapping task, where participants used a stylus to select two targets with a varying distance and width (Figure 2.10).

2. A disk transfer task, where amplitude and tolerance (i.e., target width) were controlled.

3. A pin transfer task, where the amplitude and tolerance were controlled.

The results of the experiments proved Fitts' hypothesis, which states that, the average movement time will be directly proportional to the average amount of information, if the amplitude (i.e., distance to target) and tolerance (i.e., width of target) of a task are kept constant, and subjects are instructed to perform the task as quickly as possible (Fitts 1954). Fitts concluded that as tolerance decreases or as amplitude increases, movement time increases. These results led Fitts to discover the index of difficulty. Fitts describes the reasons behind the index of difficulty as follows.

> In order to test the results against a quantitative prediction that the information output of the human motor system in any particular type of task is relatively constant over a range of amplitude and accuracy requirements, a difficulty index is needed that will specify the minimum information required on the average for controlling or organizing each movement.

Fitts' suggested that, the minimum information required for a human movement, with an average amplitude[5] (i.e., width) and tolerance (i.e., distance) is directly proportional to the logarithm of the fraction of twice the amplitude and tolerance. Fitts' mathematical formula for the index of difficulty ID is defined as

$$ID = -\log_2 \frac{W_s}{2D} \quad bits/response, \tag{2.2}$$

this formula could also be expressed as

$$ID = \log_2 \frac{2D}{W_s} \quad bits/response, \tag{2.3}$$

The value W_s is the tolerance (i.e., width of target), and D is the amplitude (i.e. distance to target). Fitts' explains the reason for using *2D* is to guarantee a positive index of difficulty (Fitts 1954).

Fitts devised another mathematical formula to express the information capacity of the human motor system as a performance rate. The index of performance IP is the ratio of average information rate to average movement time (Equation 2.4, 2.5), where MT is the average movement time in seconds.

$$IP = -\frac{1}{MT} \times \log_2 \frac{W_s}{2D} \quad bits/second, \tag{2.4}$$

which could also be expressed as

$$IP = \frac{1}{MT} \times \log_2 \frac{2D}{W_s} \quad bits/second, \tag{2.5}$$

[5] Fitts originally used A to represent the amplitude, however, in this thesis D will be used instead to avert any confusion, since several modifications of Fitts' Law used D to represent the amplitude between two targets.

One can find great resemblance between Shannon's equation for the information capacity C (Equation 2.1), and Fitts' formula for the index of performance IP (Equation 2.5), where the log expression in Shannon's formula matches Fitts' formula for the ID (Equation 2.3), and Shannon's frequency bandwidth W matches the inverse of Fitts' movement time (Equation 2.5) (MacKenzie 1991).

Movement time could be expressed in several ways, one of which is a variation of Fitts' formula for the IP that divides the index of difficulty by the index of performance (Equation 2.6). While another way to calculate movement time MT is through regression (Equation 2.7), where a is the intercept coefficient and b is the slope. The inverse of the slope b (Equation 2.8) produces another variation to Fitts' formula for the index of performance IP (Equation 2.5). These two methods produce slightly different results, due to the different approaches taken to compute the movement time. Different variations of Fitts' Law, including an ISO standard that unifies these variations into one law, are introduced in the following subsection.

$$MT = \frac{ID}{IP} \tag{2.6}$$

$$MT = a + b \times ID \tag{2.7}$$

$$IP = \frac{1}{b} \tag{2.8}$$

The above equations allow researchers to compute users' index of difficulty ID and index of performance IP, by controlling dependent variables such as movement time MT and varying independent factors such as tolerance or width of target W, and amplitude or distance to target D.

Areas of Concern

One area of concern in Fitts' Law, is the intercept coefficient a, which could be a negative value in some cases, thus predicting a negative movement time for low IDs. Another area of concern is the un–proportionality between width and amplitude (Equation 2.3), which causes an unequal increase or decrease of *ID* if one of the independent factors is changed (MacKenzie 1991). To resolve these concerns, a number of modifications to Fitts' Law have been introduced. These modifications are discussed in the following subsections.

Studies in Fitts' Law

Fitts' first experiment that led him to develop Fitts' Law in 1954 was the reciprocal tapping experiment (Fitts 1954). In the experiment, participants used two styli (1 oz., and 1 lb.), to select two rectangles with a variable width and amplitude (Figure 2.10). Results of the experiment showed that participants committed more errors with the heavier stylus, and the number of errors increased as tasks became harder. Results also showed a movement time is directly proportional to amplitude, but inversely proportional to width of target.

Another pioneering experiment that compared pointing devices was done by English et al. (1967). In a text selection experiment, English et al. compared the speed and error rate of the lightpen, joystick, mouse, knee control, and grafacon[6]. Experimental results showed that users were faster and more accurate with the mouse than any of the other devices. The authors did not investigate the effects of target width or amplitude on selection time, rather they were more concerned with the way users hold the device, their selection technique, and fatigue.

Fitts' experimental results (Fitts 1954) were the basis for one of the most important laws used in human computer interaction research, that is Fitts' Law (Equation 2.11). The first experimental evaluation of pointing devices that used Fitts' Law was done by Card et al. (1978). In their experiment, Card et al. compared users' selection time with four input devices (mouse, isometric joystick, step keys, and text keys) in highlighting pieces of text on a CRT screen. With target width, and amplitude as independent variables, the mouse was the fastest device, with the least error rate.

In an experiment to test how Fitts' Law would apply to pointing and dragging tasks, Gillan et al. (1990) conducted an experiment, which showed

[6] A grafacon is an early version of today's stylus and tablet.

that users performed pointing tasks faster than dragging tasks, and that the longer the dragging distance is the more time users spend doing the task. Results also showed that pointing time depends on both the width and amplitude of target, while with dragging tasks, the dragging time only depends on the amplitude of the target.

Another study, by MacKenzie et al. (1991), investigated users' performance with three pointing devices (mouse, stylus with tablet, and trackball) during pointing and dragging tasks. Results of the experiment confirmed Gillian et al.'s results that Fitts' Law can model pointing and dragging tasks, and that users perform pointing tasks faster with a lower error rate than dragging tasks. Users committed more errors, and spent more time performing tasks (pointing and dragging) with the trackball, than the mouse or stylus. The mouse outperformed the stylus for dragging tasks, with an *IP* of 4.0 compared to 3.6 for the stylus. However, for pointing tasks, the stylus had a higher *IP* (4.9) than the mouse (4.5).

In examining if Fitts' Law would apply to the finger-controlled isometric joystick, Douglas & Mithal (1994) compared its performance to that of the mouse. Their results showed that Fitts' Law is suitable for evaluating the isometric joystick, and that the mouse was faster by 50%. However, in another study by Zhai et al. (1997) the isometric joystick outperformed the mouse. In the study, Zhai et al. compared the performance of four pointing devices; namely the mouse, a mouse with a scroll wheel, a mouse with an isometric joystick, and a two handed input with a mouse on the dominant hand, and an isometric joystick in the other. Results showed that participants spent less time selecting targets with the two handed input, than any of the other devices. The two handed input device and the joystick were significantly faster than the mouse by 25.5% and 22.4% respectively. The mouse with a scroll wheel, on the other hand, was 8.7% slower than the standard mouse.

In a study that compared the effect of size and weight of the pointing device on its performance, Isokoski & Raisamo (2002) compared six different mice; namely Logitech iFeel, Logitech iFeel MouseMan, Microsoft Basic Mouse, Microsoft IntelliMouse, Logitech Internet Mouse, and Logitech MouseMan Wheel. Results of the study showed that the Logitech iFeel Mouse had the highest throughput (i.e., index of performance). However, there was no significant difference between the six pointing devices, thus proving that size and weight of the pointing device do not affect its performance.

The robustness of Fitts' Law also extends to eye tracking. in a target acquisition experiment, Miniotas (2000) compared the performance of an eye tracker to that of a mouse. Results of the experiment showed that participants were faster with the mouse. A linear relationship between the index of difficulty and movement time, for the eye tracker, confirmed Fitts' Law ability to predict movement time for eye gaze interaction.

2.2.2 Variations and Modifications to Fitts' Law

In this subsection, I will give an overview of early variations of Fitts' Law, and the modifications suggested by human computer interaction researchers, as well as an overview of the International Organization for Standardization (ISO) standard on the evaluation of pointing devices.

Variations of Fitts' Law

Several variations of Fitts' law (Equation 2.3) improve on Fitts' original research. The most notable and widely used variations are those done by Crossman (1957), and Welford (1968). Crossman noted that, with Fitts' experiment for a reciprocal tapping task (Fitts 1954), the intercept a yielded a negative value. To adjust the intercept, Crossman suggested balancing the ratio of amplitude to target width, in the following equation for calculating the index of difficulty (Welford 1968).

$$ID = \log_2 \left(\frac{D}{W} \right) \tag{2.9}$$

Welford (1968), proposed the addition of 0.5 to the logarithmic term (Equation 2.10). However, equations 2.9 and 2.10 yield a negative index of difficulty for overlapping targets (i.e., targets with D < $\frac{W}{2}$).

$$ID = \log_2 \left(\frac{D}{W} + 0.5 \right) \tag{2.10}$$

To constantly produce a positive index of difficulty, MacKenzie (1991) suggested the implementation of Shannon's formula for the information capacity (Equation 2.1), thus producing the following formula for the index of difficulty.

$$ID = \log_2 \left(\frac{D}{W} + 1 \right) \tag{2.11}$$

The advantages of using Shannon's formula were outlined by MacKenzie & Buxton (1992) as: (a) provides a slightly better fit, (b) exactly mimics the information theorem underlying Fitts' Law, and (c) always gives a positive rating for the index of difficulty.

Extensions to Fitts' Law

To model users' accuracy in selecting targets, Crossman (1957) suggested using the *effective width* method, by adjusting the target width such that it represents the actual spread of data rather than the expected spread of data. The new target width, effective width (W_e), corresponds to Shannon's information content H (Equation 2.12, 2.13) (Shannon & Weaver 1949, Welford 1968, MacKenzie 1991, Soukoreff & MacKenzie 2004).

$$H = \log_2 \sqrt{2\pi e} \cdot \sigma \tag{2.12}$$

$$W_e = 4.133 \cdot \sigma \tag{2.13}$$

The value σ represents the standard deviation of the distribution of users' data. MacKenzie (1991) and Welford (1968) explain that dividing 4.133 by two, gives the endpoints of a z score value of ± 2.066. Approximately 96% of the data are valid and lie within the mean, and 4% lie outside the mean (i.e., outside the target). Thus, if a data point lies outside the mean and has an error rate that is greater than 4%, then the effective width should be used to calculate the effective index of difficulty (Equation 2.14) rather than the actual target width.

$$ID_e = log_2\left(\frac{D}{W_e} + 1\right) \tag{2.14}$$

MacKenzie et al. (1991) extended Fitts' Law to cover two dimensional tasks, by investigating different methods of interpreting the width of a target, and comparing it to the status quo, where the target is at a horizontal distance from the cursor. One of the methods, called *W prime* (*W'*) takes into account target height, width, amplitude, and approach angel θ (a predetermined independent factor) to calculate the width of target (*W'*). Another method, called *smaller–of*, is only applicable for rectangular targets, and interprets the smaller of the target width and height, as the width of the target. Results of MacKenzie and Buxton's experiment showed that the smaller–of method had the least error rate, and the highest correlation (0.9501) compared to the *W'* (0.9333) and the status quo (0.8097). There was no significant difference between the *W'* and smaller–of methods, however there was a significant difference between both the *W'* and smaller–of methods, and the status quo. The smaller–of method has the advantage of using less parameters than the *W'* method, but it is only applicable to rectangular targets. Therefore, depending on the experimental conditions, the researcher should decide on which method to use, specially since there is no significant difference between the two methods.

Accot & Zhai (2003) investigated the effects of varying the width and height of the target, in the smaller–of model, on target acquisition time and performance. Their results showed that height of the target does not have an effect on the acquisition time, if target width is smaller than target height. However, both width and height affect acquisition time, if target width is greater than target height. Therefore, to accurately model any two dimensional movement task, Accot and Zhai proposed the following three parameter Euclidean model, where η represents the weight of the target height.

$$T = a + b \cdot log_2\left(\sqrt{\left(\frac{D}{W}\right)^2 + \eta\left(\frac{D}{H}\right)^2} + 1\right) \tag{2.15}$$

Murata & Iwase (2001) extended Fitts' Law to three dimensional tasks. In their experiment, they found a significant difference between movement time and direction, however, they also found inconsistencies in the time to acquire targets at opposite ends of the interface. Thus, they concluded that the current form of Fitts' Law (Equation 2.11) is not applicable to three dimensional movement, since it does not account for movement direction. Further analysis showed that movement time, to acquire targets at different angles (0°, 45°, 90°, 35°, 180°, 225°, 270°, and 315°) follow a sinusoidal wave shape. Therefore, Murata and Iwase modified Fitts' Law to include a sinusoidal function of the angle, at which the target is positioned (Equation 2.16). The value c is a constant, determined through regression.

$$ID = log_2\left(\frac{D}{W} + 1.0\right) + c\sin\Theta \tag{2.16}$$

The modification to Fitts' Law proved successful, as a linear relationship between movement time and index of difficulty was found, as well as a higher correlation than the traditional Fitts' Law model.

MacKenzie (1991), however, suggested that if the user approaches the target from top or bottom (i.e., the mouse crosses the top or bottom edge of a rectangular target) at an angle, then target width could be represented as $W' = \left(\frac{W}{\cos\theta}\right)$, and if the user is approaching the target from the sides, then target width could be represented as $W' = \left(\frac{H}{\sin\theta}\right)$.

ISO 9241-9 standard (ISO 2000) recommends the use of circular targets arranged in a circle (Figure 2.11), when evaluating pointing devices, thereby, reducing the number of parameters needed in measuring the index of difficulty and movement time.

ISO 9241-9

The ISO standard is called *Ergonomic requirements for office work with visual display terminals* VDT*s, part 9 requirements for non-keyboard input devices.* The standard was written, such that pointing device designers would take into account measures such as users' comfort, limitations, and safety. Douglas et al. (1999) state that all pointing devices sold in Europe are required to conform to the ISO standard.

One of ISO's recommendations, is the use of Fitts' Law and the Steering Law in evaluating pointing devices. However, there have been a number of variations, and recommendations to Fitts' Law. The ISO standard merges these variations into one law, such that future research is consistent and comparable (Douglas et al. 1999, Soukoreff & MacKenzie 2004, Zhai 2004*a*). The standard recommends the following:

- Evaluating the pointing device performance in dragging and selection tasks. Selection tasks would be multi-directional, with a circular arrangement of targets (Figure 2.11), where W is the width of target, D is the distance to target, and the numbers 1, 2, and 3 represent the path taken by the user.

- Using the effective width W_e method (Equation 2.13) rather than the actual target width.

- Using throughput[7] TP (Equation 2.17) to account for the the speed and accuracy of the device.

$$TP = \frac{ID_e}{MT} \tag{2.17}$$

- Assessing users' experience while using the device, through surveys to gather information such as comfort, effort, and fatigue.

Soukoreff & MacKenzie (2004) argue that new and improved evaluation techniques, as well as the ISO standard are needed to maintain consistency among researchers. Hence, they propose a set of seven recommendations, as a supplement to the ISO 9241-9 standard, for researchers using Fitts' Law to evaluate pointing devices. These are:

1. Using Shannon's formula for calculating the index of difficulty (Equation 2.11), since it would always yield a positive index of difficulty.

[7] Throughput is identical to the index of performance suggested by Fitts (1954).

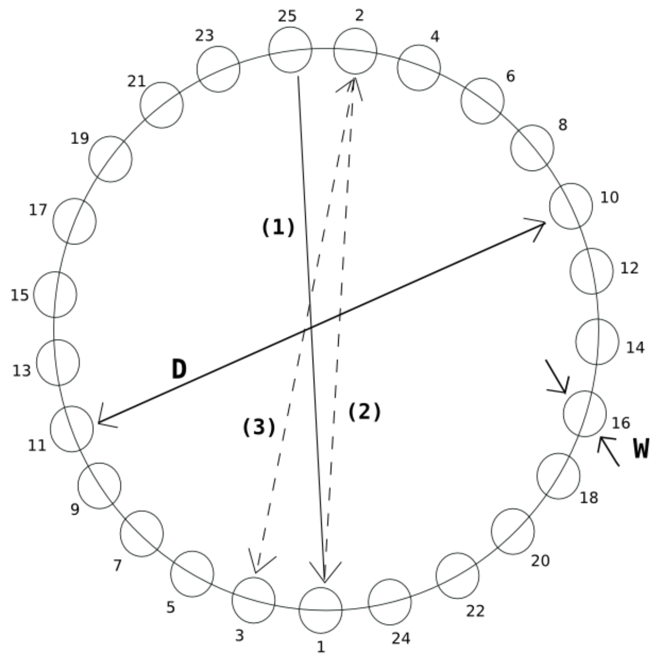


Figure 2.11: The circular arrangement of targets, recommended by ISO 9241-9 standard (Soukoreff & MacKenzie 2004).

2. Use a wide range of indices of difficulties (from 2 to 8) to increase the knowledge of the users' ability, and to gather a wide range of data for producing a better fit.

3. Record users' endpoint selection position and error rate.

4. Use the adjustment of accuracy method to measure the effective index of difficulty (Equation 2.14).

5. Examine the goodness of fit (i.e., the linear relationship between the index of difficulty and movement time), to test the applicability of Fitts' Law.

6. Remove any outliers, and limit the movement time predictions to the range of indices of difficulty used in the experiment (i.e., no predictions of movement time should be made for an *ID* value that lies outside the experimental conditions).

7. Calculate the throughput (Equation 2.17) for each user to compare devices or experimental conditions, if needed.

However, in a study that examined the effect of varying the nominal width W and the effective width W_e on task parameters, (Zhai, Kong & Ren 2004) found that the effective width method weakened the correlation between movement time and index of difficulty.

Throughput Measurement Methods

Several methods have been developed to measure the throughput of a pointing device, however each method produces different results. Hence, the difficulty of comparing previous evaluations of pointing devices (Zhai 2004*a*). One example is MacKenzie & Soukoreff (2003) reanalysis of Card et al. (1978) experimental results, in which Card et al. produced a throughput of 10.3 bps, while MacKenzie and Soukoreff produced a throughput of 2.65 bps using the ISO standard recommended method of calculating the throughput (Equation 2.17).

After Fitts' original formula for the index of performance (Equation 2.5), Fitts & Radford (1966) devised another formula for the index of performance, as the inverse of the slope (Equation 2.8). ISO 9241-9 standard, on the other hand, recommended two ways to measure throughput; (a) using the effective index of difficulty (Equation 2.17), and (b) using the ratio of the mean of indices of difficulty to the mean of movement times (Equation 2.18).

Another way of calculating throughput is explained by Soukoreff & MacKenzie (2004), where the mean of means is calculated for every subject (i.e., the mean throughput at each index of difficulty), then averaging the throughput for all subjects to produce the final throughput (Equation 2.19). In the equation, y represents the number of subjects, while x represents the number of movement conditions.

$$TP = \left(\frac{\overline{ID}}{\overline{MT}} \right) \tag{2.18}$$

$$TP = \frac{1}{y}\sum_{i=1}^{y}\left(\frac{1}{x}\sum_{j=1}^{x}\frac{ID_{e_{ij}}}{MT_{ij}}\right) \tag{2.19}$$

These different methods of measuring throughput begs the question, which of these methods is the right one? Zhai (2004*a*) analysed these methods, and concluded that the inverse of the slope or the information aspect of pointing performance b (Equation 2.8) should be used to calculate the throughput of the device. To solve the problem of comparing research results based on different measurement techniques (i.e., techniques of measuring throughput), Zhai introduced the following three remedies:

1. Standardization of ID set in testing: a standard set of IDs, such as 2, 4, 6, and 8, would cover a wide range of human motion capabilities (ISO 2000), and facilitate comparisons between different studies.

2. Return to two parameter Fitts' Law modeling: the intercept a, and the slope b, or as Zhai (2004*a*) explains, the information-independent, and the information aspect of pointing performance, would provide information such as the impact of the pointing device on target selection, and the throughput of the device.

3. A clear exclusion if any non-information aspect of pointing from Fitts' Law modeling: outliers, such as homing time, and button click time, should be removed to reduce any noise that might affect the fit of the regression line.

For the reasons mentioned above, and to more accurately understand the reasons that might affect the regression line, I will use the nominal target width, and the inverse of the slope (Equation 2.8) to calculate the index of difficulty, and to measure and compare the throughput of the pointing devices used in this experiment.

2.2.3 Steering Law

Fitts' Law does not apply to all classes of movement, such as dragging, writing, drawing, and navigating nested menus, all of which could be described as trajectory based movement. In 1997, Accot and Zhai used a tunnel analogy (Figure 2.12) to model trajectory based movement, and proposed a new model, which they called the Steering Law. Accot and Zhai hypothesized that the time the user takes to draw a line inside a tunnel (i.e., traverse a tunnel), depends on the length and width of the tunnel (Accot & Zhai 1997). To test their hypothesis, Accot and Zhai performed the following four experiments.

1. Goal passing: in which users were asked to use a stylus to pass two goals (Figure 2.13) by traversing through the tunnel. Results showed that the steering model behaved in a similar fashion to Fitts' Law, with a linear relationship between movement time and index of difficulty (Accot & Zhai 1997). This experiment led Accot and Zhai to the conclusion that, in a two goal passing task, the Steering Law (Equation 2.20) is similar to Fitts' Law (Equation 2.11).

$$ID = log_2 \left(\frac{D}{W} + 1 \right) \tag{2.20}$$

2. Tunnel steering: Accot and Zhai included more goals into the first experiment, by first dividing the distance between goals into two (i.e., three goals) which produced the following equation.

$$ID = 2\ log_2 \left(\frac{D}{2W} + 1 \right) \tag{2.21}$$

   This motivated the authors to experiment with N number of goals (Equation 2.22). Thus proving that as the number of goals increases, users would be more careful, and hence would spend more time traversing the tunnel.

$$ID_N = N\ log_2 \left(\frac{D}{NW} + 1 \right) \tag{2.22}$$

   Further analysis showed that for a tunnel with an infinite number of goals (Figure 2.12) the index of difficulty is not directly proportional to the logarithm of the ratio between distance to target and width of

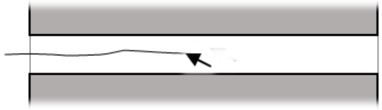


Figure 2.12: A trajectory movement task (Accot & Zhai 1997).

Figure 2.13: Goal passing experiment (Accot & Zhai 1997).

target, but rather directly proportional to the ratio of distance to width of target (Equation 2.23). Thus, participants' average movement time could be expressed by equation 2.24.

$$ID = \frac{D}{W} \tag{2.23}$$

$$MT = a + b \times \frac{D}{W} \tag{2.24}$$

3. Narrowing tunnel: The applicability of the Steering Law to a tunnel with variable width (Figure 2.14) was tested by Accot & Zhai (1997). Their results showed a linear relationship between movement time and index of difficulty, thus, proving that the Steering Law does apply to the narrowing tunnel. The index of difficulty for the entire tunnel was calculated by dividing the tunnel into smaller rectangles with distinct widths. Therefore, by calculating the index of difficulty for each distinct width, the index of difficulty for the entire tunnel could be calculated

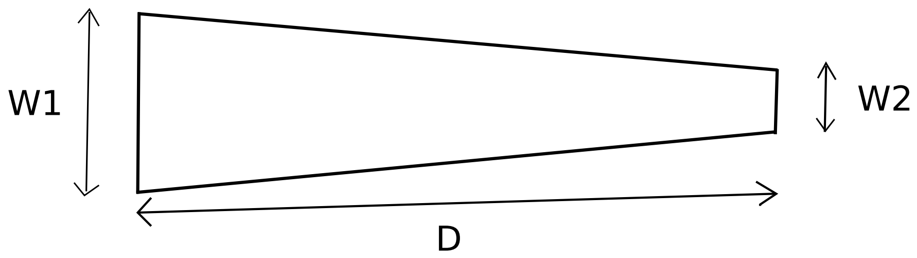


Figure 2.14: A Tunnel with a narrowing width (Accot & Zhai 1997).

using Equation 2.25, which could be simplified to Equation 2.26.

$$ID_{\infty} = \int_0^D \frac{dx}{W(x)} = \int_0^D \frac{dx}{W_1 + \frac{x}{D}(W_2 - W_1)} \tag{2.25}$$

$$ID_{NT} = \frac{D}{W_2 - W_1} \ln \frac{W_2}{W_1} \tag{2.26}$$

To extend this approach to complex tunnels (Figure 2.15(a)), the authors calculated the index of difficulty for each point in the curvilinear abscissa s, and integrated the sum of the indices of difficulty to produce the following generic index of difficulty for the entire path C (Equation 2.27). Movement time along path C can thus be calculated by using Equation 2.28.

$$ID_C = \int_C \frac{ds}{W_s} \tag{2.27}$$

$$T_C = a + b \int_C \frac{ds}{W_s} \tag{2.28}$$

For a straight tunnel with constant width (Figure 2.15(b)), movement time in Equation 2.28 could be reduced to the following equations.

$$T_C = a + b \times \frac{1}{W} \int_C ds \tag{2.29}$$

$$T_C = a + b \times \frac{D}{W} \tag{2.30}$$

An example of straight tunnels is cascading menus, where the movement time is modified to accommodate horizontal and vertical tunnels (Equation 2.31). In which, n represents the number of sub-menus traversed to reach the target, w represents the width of the menu, and h is the height of the sub-menu item (Accot & Zhai 1999).

$$T_n = a + b \times \frac{nh}{w} \; + \; a + b \times \frac{w}{h} \tag{2.31}$$

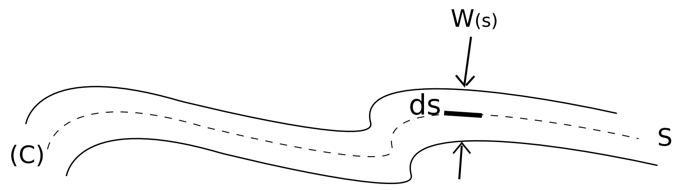
4. Spiral tunnel: After the success of the Steering Law with horizontal and narrowing tunnels, Accot and Zhai examined if the Steering Law would apply to spiral tunnels (Figure 2.15(d)). Participants were asked to use a stylus to traverse the spiral tunnels. The number of spirals (n), and the width of the spiral (ω) were varied to compute different indices of difficulty (Equation 2.32). Results of the experiment showed a linear relationship between movement time and index of difficulty, thus confirming the applicability of the Steering Law to spiral tunnels.

$$ID_{S_{n,\omega}} = \int_{2\pi}^{2\pi(n+1)} \frac{\sqrt{(\theta+\omega)^6 + 9(\theta+\omega)^4}}{(\theta+2\pi+\omega)^3 - (\theta+\omega)^3} \cdot d\theta \tag{2.32}$$

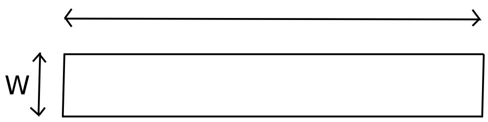
The four experiments confirmed the hypothesis that the width and length of the tunnel are directly proportional to participants' movement time. Thus confirming the applicability of the Steering Law to trajectory based tasks, and its ability to predict participant's completion time.

Studies in Steering Law

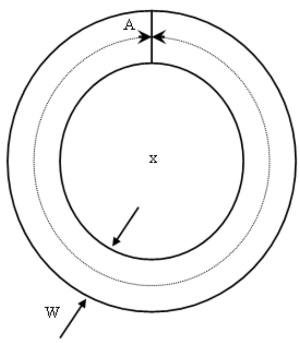
To investigate if scaling would affect users' performance in Steering Law tasks, Accot & Zhai (2001) conducted an experiment comparing users' performance in steering through tunnels, with different indices of difficulty, at five different scaling levels. The results showed an inverted U-shaped perfor-



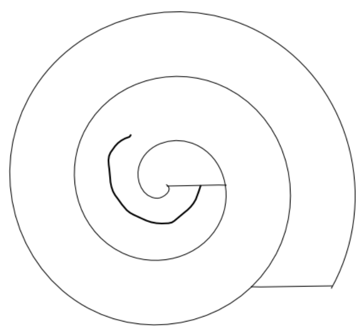
(a) A constrained trajectory Tunnel



(b) Linear tunnel



(c) Circular tunnel



(d) Spiral tunnel

Figure 2.15: Different shapes of tunnels (Accot & Zhai 1997).

mance scale with a significant difference between scales. Moderate scales had the highest index of performance, and the shortest movement time, while, extreme scales had the lowest index of performance and longest movement time, since they were either too small for the user's motor precision, or too large to reach. The study also showed that two tasks with the same index of difficulty but at two different scales would have a different movement time, hence proving that scaling affects users' index of performance in Steering Law tasks.

Dennerlein et al. (2000) introduced a new computer mouse that uses force-feedback, by adding a force-field, to pull the mouse cursor to the center of the tunnel. Results of the experiment showed a 52% increase in steering time with force-feedback. However, one of the disadvantages of force-feedback occurs when the users steers through the wrong path (for example, in selecting a menu item), as a result users may experience frustration in steering away from the force-field. Results also showed a linear relationship between index of difficulty and movement time for vertical and horizontal tasks, with the horizontal movement having a faster movement time than vertical movement. Thus, proving the applicability of the Steering Law for horizontal and vertical tasks.

In an effort to examine the validity of the Steering Law in virtual reality environments, Zhai, Accot & Woltjer (2004) conducted an experiment, in which the participant would use a driving simulator to steer a virtual car through straight and circular paths with a variable length and width. Results of the experiment showed a linear relationship between the ratio of distance to width (i.e, index of difficulty of the path) and the mean steering time, thus confirming the applicability of the Steering Law to locomotion in virtual reality environments.

Modifications to the Steering Law

Ahlstrӧm (2005) devised an alternative to the Steering Law for tunnels that include horizontal and vertical paths (for example, cascading menus). Ahlstrӧm merged Fitts' Law and the Steering Law into one formula (Equation 2.33), where Fitts' Law is applied for vertical movement, and the Steering

Law applied for horizontal movement. Ahlstr$\ddot{o}$m's hypothesis was: the total index of difficulty for the entire path (ID_T) could be calculated by adding the index of difficulty for the vertical movement (ID_{V_m})[8] and the index of difficulty for horizontal movement(ID_{H_m}). In the same paper, Ahlstr$\ddot{o}$m describes a new approach to improve selection from cascading pull-down menus. The new approach uses a cursor wrapping algorithm to apply a force-field, which pulls the cursor toward a pull-down sub-menu, in the case of a parent menu (i.e, a menu that includes a sub-menu).

To evaluate the new force-field, and to test the applicability of the new model (Equation 2.33), Ahlstr$\ddot{o}$m conducted an experiment to compare movement times for the, mouse, touchpad, and trackpoint, in selecting items from cascading pull-down menus, with and without the force-field. Results of the experiment showed that the new force-field improves users' selection time by 18%. Results also showed a linear relationship with a correlation of ($r^2 \geq 0.904$) between device and menu type, thus confirming the validity of the new model to predict selection times for cascading pull-down menus.

$$ID_T = ID_{V_m} + ID_{H_m} \tag{2.33}$$

Kulikov et al. (2005) made an attempt to improve the robustness of the Steering Law by increasing the correlation between the index of difficulty and movement time. To increase the correlation, Kulikov et al. suggested the use of the effective width W_e (Equation 2.13) instead of the nominal width W for calculating the steering index of difficulty. Experimental results showed a higher correlation using the effective width (0.961 for the mouse, and 0.936 for the stylus) than with the nominal width (0.910 for the mouse, and 0.914 for the stylus).

Another Steering Law model combines both Fitts' Law and the Steering Law for tasks that require pointing and steering (Equation 2.34), where ID_S is the index of difficulty for the steering task (Equation 2.23) and ID_T is the Fitts' index of difficulty (Equation 2.11) (Dennerlein et al. 2000).

$$MT = a + b \cdot ID_S + c \cdot ID_T \tag{2.34}$$

[8] The number of sub-menus traversed to reach the target, is represented by m.

Kulikov & Stuerzlinger (2006) explain that the model (Equation 2.34) is complex since it contains a third parameter that will always increase the correlation. Thus, Kulikov et al. propose a simpler model (Equation 2.35), that only uses two independent variables.

$$MT = a + b \times (ID_S + ID_T) \tag{2.35}$$

All Steering Law studies performed so far (Accot & Zhai 1997, 1999, Dennerlein et al. 2000, Accot & Zhai 2001, Zhai, Accot & Woltjer 2004, Kulikov et al. 2005, Ahlström 2005) only tested the applicability of the law in two shapes of tunnels, straight and circular tunnels. Pastel (2006) studied the applicability of the law, and possible extensions, to tunnels with corners. Pastel explains that, both Fitts' Law and the Steering Law are required to model the index of difficulty for a tunnel with corners, which means that the total index of difficulty is directly proportional to Fitts' index of difficulty, and Steering index of difficulty (Equation 2.36).

$$ID_C = ID_S + ID_F = \tau_S \left(\frac{D}{W}\right) + \tau_F \ln \left(\frac{D}{W}\right) \tag{2.36}$$

$$MT_C = a + b \cdot ID_S + c \cdot ID_F \tag{2.37}$$

Equation 2.37 models the movement time through the tunnel, where the value τ_S is the participants steering time constant, τ_F is the participants Fitts' time constant, a, b, and c, are empirical values determined through regression, ID_S is the index of difficulty for the steering task, and ID_F is the index of difficulty for the Fitts' task.

2.3 Conclusion

In this Chapter, I discussed the history of pointing devices, and the development of two laws used in evaluating pointing devices, Fitts' Law and the Steering Law.

There has been several variations to Fitts' law each with its own advantages and disadvantages. These variations along with areas of concern, and modifications to Fitts' law were addressed. As well as the formulation of the ISO 9241-9 standard to maintain consistency among researchers.

How Accot and Zhai developed the Steering law, and how the formula for the index of difficulty changes depending on the tunnel shape were addressed, as well as modifications to the law, and the possibility of combining both Fitts' law and the Steering law to model the index of difficulty for tunnels with corners.

Chapter III

Overview of Swiftpoint

Swiftpoint is a computer pointing device, invented by Simtrix, a company based in Christchurch, New Zealand. Swiftpoint is designed to help mobile computer users interact easily with graphical user interfaces GUIs in constrained spaces, such as on a train, or plane. In this Chapter, I will outline the key features of Swiftpoint, describe its features and expected advantages, ergonomics, specifications, and finally Swiftpoints' near future.

3.1 Key Features

Swiftpoint has similar properties to those of the mouse, such as pointing, clicking, and scrolling. However, the shape of Swiftpoint is completely different from the mouse. Unlike the mouse, Swiftpoint is very small and is not held in the palm of the hand; it rather requires the thumb to hold it and move it around (Figure 3.1), where the index and middle fingers are used to press on the primary and secondary mouse buttons respectively. The small size of Swiftpoint allows it to be held in a similar fashion to the pen. Thus, combining the advantages of both the stylus and mouse. It can be

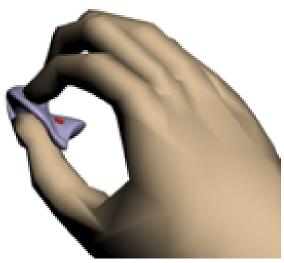
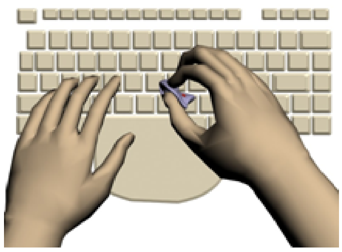
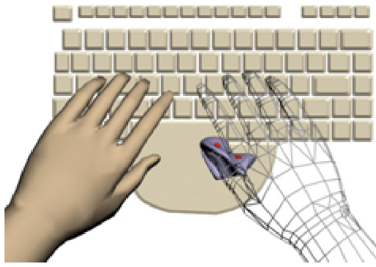


Figure 3.1: Only the thumb is needed to hold and move Swiftpoint, and the index and middle fingers to click on the mouse buttons (Simtrix 2004).



(a) Swiftpoint used on top of the keyboard keys.



(b) Swiftpoint used on top of the extended spacebar.

Figure 3.2: Swiftpoint on a flat keyboard (Simtrix 2004).

used for drawing and writing, moreover it can be easily moved on any flat surface, such as a flat keyboard, or the custom designed Swiftpoint keyboard with an extended spacebar (Figure 3.2). A flat keyboard, similar to that of the laptop, would be best suited for Swiftpoint, while an extended spacebar, though not necessary, would give the user more space and freedom to move Swiftpoint using his or her thumb. Swiftpoint was designed to cover three to four keys, thus, preventing any inadvertent activation of keys, while using Swiftpoint on the keyboard.

3.2 Product Description

There exist a number of models for Swiftpoint each with different features, such as scroll wheel or pen-like model. However, the standard Swiftpoint model (Figure 3.3) that was used in the experimental evaluations had two buttons, which resemble the primary and secondary buttons of the mouse; a sensor underneath that maps the location of Swiftpoint, and a thumb hold.

3.3 Expected Advantages Over Existing Pointing Devices

- Eliminating the transition time (i.e. the time the user takes to move his or her hands between the keyboard and pointing device): Using common Microsoft Windows applications such as Microsoft Word or Internet Explorer, requires the user to constantly switch their hands between the keyboard and pointing device. To reduce this transition

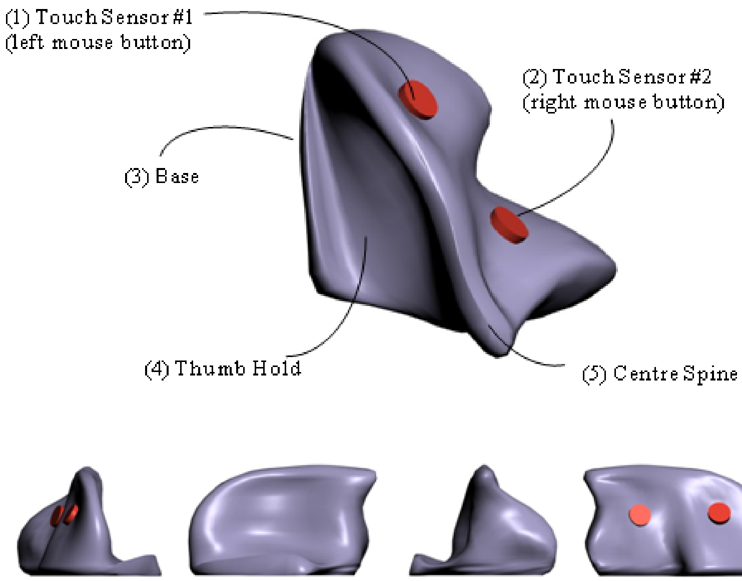


Figure 3.3: Different views (aerial, top, front, left, rear, and right) of Swiftpoint Swiftpoint on a flat keyboard (Simtrix 2004).

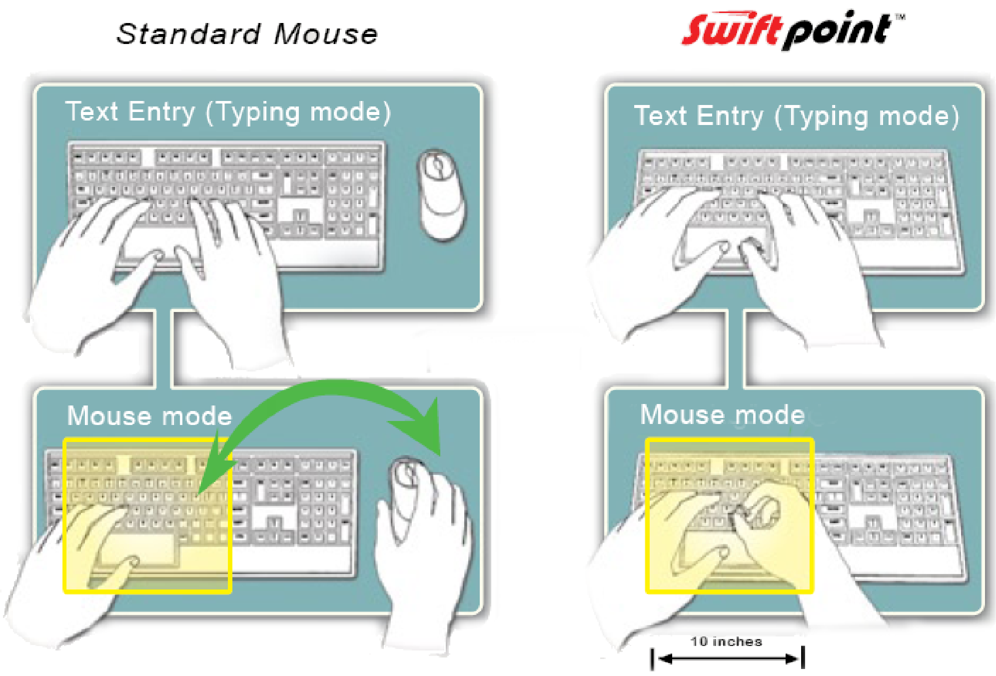


Figure 3.4: Hand movement of mouse vs. Swiftpoint (Simtrix 2004).

time, some users resort to using keyboard shortcuts. Since Swiftpoint can be used on top of the keyboard (Figure 3.2), and since it forces the user to keep his or her hands on top of the keyboard most of the time (Figure 3.4) it eliminates the transition time between pointing device and keyboard (Simtrix 2004).

- Higher precision: Tasks that require fine movement or high precision, such as using the mouse to write or draw are challenging, due to the mouse's size and shape, which forces the user to use his or her hand rather than his fingers to hold the mouse. However, with Swiftpoint the user holds it with his fingers in a similar fashion to the pen, and can use it as a pen (Figure 3.5) for tasks that require high precision.

- Economical and requires no space: Laptop users travelling on a plane, or a train often pack a pointing device for the trip, and would struggle to place the mouse on the food–tray provided. With Swiftpoint, the user does not need to worry about where to place Swiftpoint, since it is small (1/10 the size of the mouse) and can be used on top of the keyboard. Swiftpoint is also economical, and does not require any batteries or a recharging (Simtrix 2004).

3.4 Implementation and Modes of Operation

Swiftpoint could be implemented in two different ways as follows.

1. Swiftpoint on a laptop: in which case, a tablet would be embedded underneath the keyboard;

2. Swiftpoint on a desktop: in which case, the keyboard would be flat, similar to that of a laptop, and a tablet would be embedded underneath the keyboard, or the user could use a separate tablet beside the keyboard.

Swiftpoint has two main modes of operation, depending on the model used and purpose it is used for, these are:

- Navigation mode: for tasks such as, document or web navigation, where primary and secondary mouse buttons and the scroll wheel (if present) are used.

- Digital ink mode: for tasks such as, drawing or writing, in which case Swiftpoint would be tilted (Figure 3.5, 3.6) and used as a pen. The nib point sensor would activate as it is moved closer to the tablet surface and the secondary, and primary button mouse buttons could be used as an eraser button or as configured by the user (Simtrix 2004).

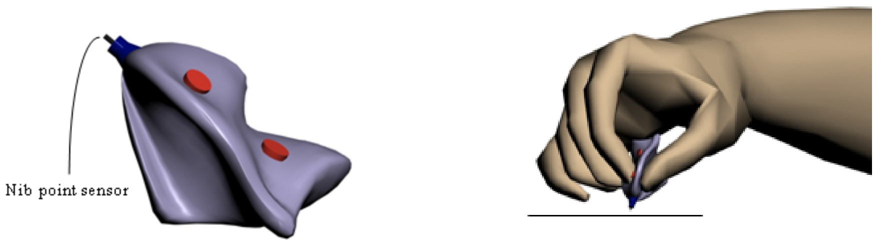


Figure 3.5: Swiftpoints' Digital Ink mode (Simtrix 2004).

3.5 Ergonomics

As the number of computer users increases, the number of computer related injuries, such as carpel tunnel syndrome and repetitive strain injury (*RSI*), increases. Most of these injuries result from an incorrect posture while sitting on the computer, such as positioning the keyboard and mouse away from each other.

There has not been any ergonomic study for Swiftpoint, but since Swiftpoint is held in a similar fashion to the pen (Figure 3.6), it is expected that it would have the same advantages and disadvantages as those of the pen. Hence, previous ergonomic studies of the pen will be used to predict that of Swiftpoint. An independent study published by Global Ergonomic Technologies (1998) compared the posture of eight participants using the mouse and Wacom pen. The study showed that the pen outperformed the mouse

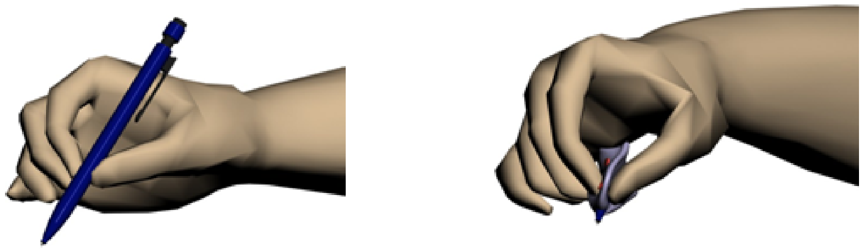


Figure 3.6: Swiftpoint is held in a similar fashion to the pen (Simtrix 2004).

with "less posture deviation and no hand pronation from neutral" (Global Ergonomic Technologies 1998). Therefore, it is expected that Swiftpoint will have no pronation and less posture deviation from neutral than that of the mouse.

Swiftpoint has the advantage of forcing the user to keep his or her hands on the keyboard, while typing or browsing, rather at the side of the keyboard. Thus eliminating hand movement between keyboard and mouse, and therefore complying with the U.S. Department of Labor occupational safety recommendations, which states that pointing device should be kept in front of the user rather that at the side of the keyboard (U.S. Department of Labour, Occupational Health and Safety Administration 2000).

3.6 Swiftpoints' Specifications

During the experiments, discussed in Chapters 4 and 5, Swiftpoint (Figure 3.3) was used with a Wacom CintiqPartner tablet that uses an analog W8001 integrated circuit (Wacom 2001*b*), and Penabled technolgy, which is an electro-magnetic resonance technology invented by Wacom, to send and receive the position of the pen (Wacom 2001*a*).

Swiftpoint has an identical transmitter to Wacoms' pen. The pen communicates with the tablet by sending a single signal at a given frequency that is detected by the digitizer in the tablet (Figure 3.8) and translated to the position of the pen. The circuit in the pen has a different frequency for every action performed by the pen (for example, a button pressed), and changes its frequency accordingly. The digitizer inside the tablet recognizes these

Figure 3.7: Wacom CintiqPartner tablet (Wacom 2006).

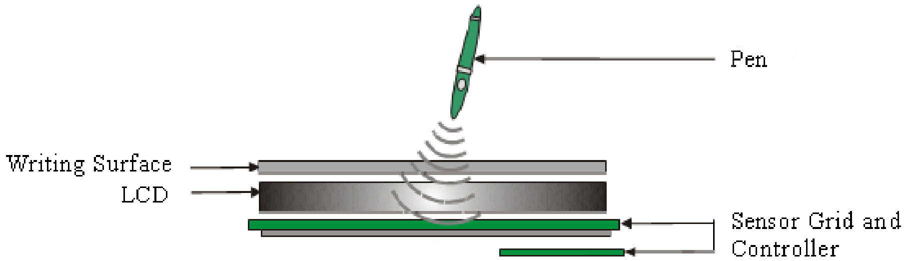


Figure 3.8: A pen transmitting a signal to the digitizer inside the tablet (Finepoint Innovations 2004).

frequencies and translates them into preconfigured responses before sending them to the PC (Finepoint Innovations 2004).

3.7 Future of Swiftpoint

There are several future designs for Swiftpoint (Figure 3.9) that range from a one button device to one with an attached pen. One design in particular (Figure 3.10) will be marketed soon to major companies, such as Toshiba, Microsoft, and Wacom. This model will have the same circuit as the one found in a pen, and will thus require a tablet (either beside the keyboard, or embedded underneath the keyboard) to capture the position and signals sent by the transmitter inside.

Future designs are expected to use more advanced sensors, such as EPOS,

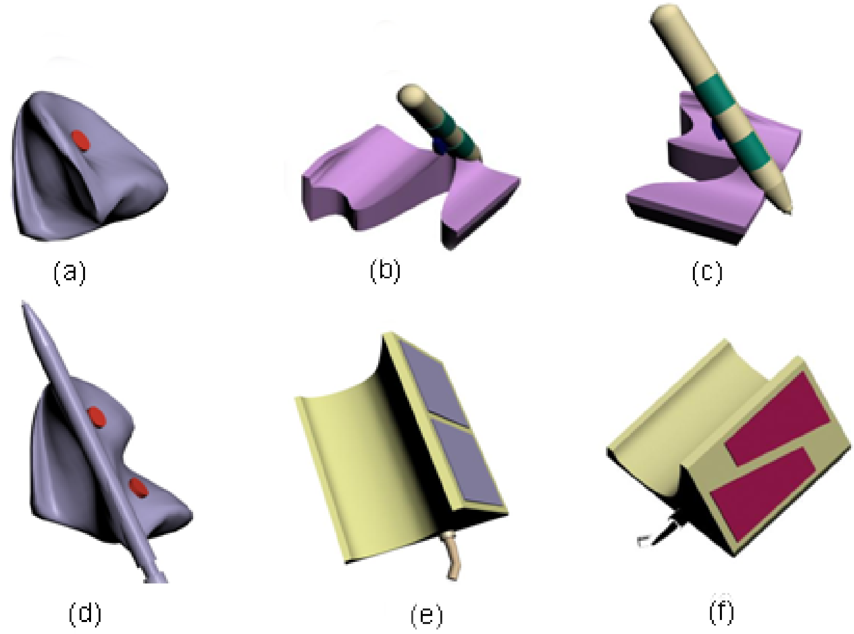
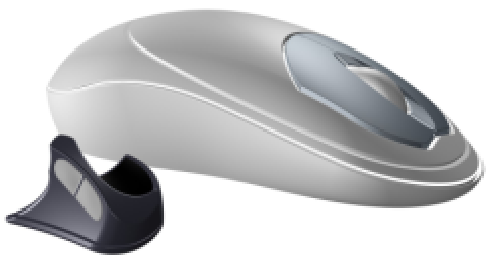


Figure 3.9: Possible future Swiftpoint models (Simtrix 2004).



(a) The new Swiftpoint model compared to a standard computer mouse.

(b) A right view of the new Swiftpoint model.

(c) A left view of the new Swiftpoint model.

Figure 3.10: The new Swiftpoint model (Simtrix 2004).

which uses ultrasonic waves to transmit data between two or more devices. The receiver in turn uses the signal to estimate time of travel (i.e., the time the wave takes) from the terminal to the receiver. Thus calculating to pin point accuracy the position of the transmitter or pen (EPOS 2005).

Another alternative is to use laser technology to detect the movement of Swiftpoint, in which case Swiftpoint would move on any surface and would not need a tablet to capture the signals sent by the transmitter.

Chapter IV

Fitts' Law Experiment

The primary objective of this experiment is to determine if Swiftpoint is a suitable device for pointing tasks. To achieve such an objective, I will apply both Fitts' Law, and the recommendations of ISO 9241-9 standard (Douglas et al. 1999, ISO 2000) to test the speed and accuracy of Swiftpoint against common pointing devices, in a target acquisition experiment.

Since Swiftpoint was designed primarily for mobile computers (such as, laptops), it is essential to compare it against devices of similar nature, such as the touchpad, isometric joystick, mouse, trackball, and stylus. However, due to a 40 minute time restriction before participants experience fatigue and boredom, only three pointing devices were selected for the experiment.

Device selection was based on ubiquity with mobile computers, and performance in previous research experiments. Since the mouse is the most popular (Zhai 2004*b*) and efficient pointing device (Card et al. 1978, Douglas & Mithal 1994, MacKenzie et al. 2001), it was selected as the control for the evaluation. Even though the touchpad was not the most efficient device (MacKenzie et al. 2001), it was also selected for the experiment because of its ubiquity with laptop computers. Some laptop computers come with an isometric joystick, however, previous studies have consistently shown that the isometric joystick had the lowest throughput among devices (Card et al. 1978, Douglas & Mithal 1994, MacKenzie et al. 2001). Therefore, the isometric joystick was excluded from the experiment. The trackball, and stylus were also excluded from the experiment due to time limits, and their high error rate (MacKenzie 1991, MacKenzie et al. 1991).

Section 4.1 discusses the experimental method, including information about participants recruited, apparatus, experimental procedure, and design. While section 4.2 presents results and analysis of the experiment. Discussion and conclusion are presented in sections 4.3 and 4.4 respectively.

4.1 Experimental Method

4.1.1 Participants

Fifteen computer science postgraduate students (eleven males and four females), with an average age of 23 years, participated in a one-to-one experiment. All participants were right-handed, and used the mouse extensively on a daily basis. Participants were rewarded with a $20 Warehouse voucher after finishing the two experiments.

4.1.2 Apparatus

The experiment was conducted on a Windows XP machine, with an AMD Athlon 64 3200+ CPU, 1GB of RAM, and a GeForce 6600 GT graphics card. The monitor was a 19 inch Compaq 9500, with a resolution of 1600×1200 pixels (111 dpi) with a viewable screen width and height of 36cm and 27cm, at a refresh rate of 75 Hz.

The three pointing devices[1] used in the experiment were:

- A mouse: Microsoft IntelliMouse (Figure 4.1(a)), with five buttons, scroll wheel and optical sensors.

- A touchpad: Cirque Smart Cat (Figure 4.1(b)), with four buttons.

- Swiftpoint (Figure 3.3), with two buttons. A tablet was used to capture the movement of Swiftpoint, and convert it to on-screen pointer movement.

Swiftpoint was used with a Wacom CintiqPartner tablet (Figure 3.7), since a laptop with an embedded tablet was not available at the time of the experiment. The tablet's dimensions were 660×243×13.9 mm, while that active area was 204.8×153.6 mm. The Wacom CintiqPartner tablet uses the analog W8001 integrated circuit (Wacom 2001*b*), and Penabled technolgy, which is an electro-magnetic resonance technology invented by Wacom to send and receive the position of the pen on the tablet (Wacom 2001*a*).

[1] Only the primary and secondary buttons were activated in each device, however, participants were only required to use the primary button for target acquisition tasks.

(a) Microsoft IntelliMouse. (b) Wacom Smart Cat touchpad.

Figure 4.1: Devices used for comparison against Swiftpoint (Microsoft 2005, Safe Computing 2006).

To ensure that all participants conducted the experiment in similar conditions, the three pointing devices were configured to use the default control-display gain values set by the Microsoft Windows XP operating system.

4.1.3 Procedure

The interface for this experiment was modeled after the ISO 9241-9 recommendations (Figure 2.11). The experiment consisted of a total of six blocks of tasks for every device, where a block consists of clicking on a series of 26 targets. Every block has a different index of difficulty (3.17 – 6.98), as determined by two circle diameters (300, and 500 pixels) and four target widths (4, 8, 19, and 34 pixels). Participants would spend around four minutes with each device, and take a total of 20 minutes to complete the whole experiment (including practice tasks).

The experimental interface (Figure 4.2) consisted of a circular arrangement of 26 red targets, two buttons on the top left corner (Practice or Experiment[2], and Finish), and an error rate counter on the top right corner. A task would require the participant to click on the illuminated (green) target.

[2] The Practice or Experiment button changed depending on the nature of the task at hand. The button displayed Practice during the practice tasks, and Experiment during the experimental tasks.

Once a target is clicked, the target is deactivated (turns red) and the opposite target is illuminated, thus steering the participant through each block of tasks. Participants' speed, error rate, index of difficulty, distance, and target width, were logged for further analysis.

At the beginning of the experimental session, a brief overview was given to each participant before he or she signed a consent form (Appendix C), and a non-disclosure agreement, followed by a demonstration of the evaluation tasks and an explanation of each device and how to use it. Participants were given the following instructions.

- Adjust the position of the screen, chair, and pointing device, to make yourself comfortable.
- Carry out the tasks as fast and as accurately as possible.
- Take a break[3] only after finishing a block of tasks (each block should be done in a continuous and constant manner).
- Only use the primary button in Swiftpoint, touchpad, and mouse, to click on a target.
- Click only once on the target as a double click or any click outside the illuminated target is counted as an error; a gentle sound is produced if an error is committed.
- Redo the task if an error is commited.
- Stay as close as possible to a 4% error rate, and be slower and more accurate if the error rate exceeds 4%, and vice versa.

Pointing devices were exposed to each participant in random order. After the demonstration, a message was displayed informing the participants to plug-in the appropriate pointing device, and click on the Practice button to start the practice tasks. Another message was displayed after participants finished the

[3] A message was displayed after every block of tasks instructing the participant to take a short break if needed.

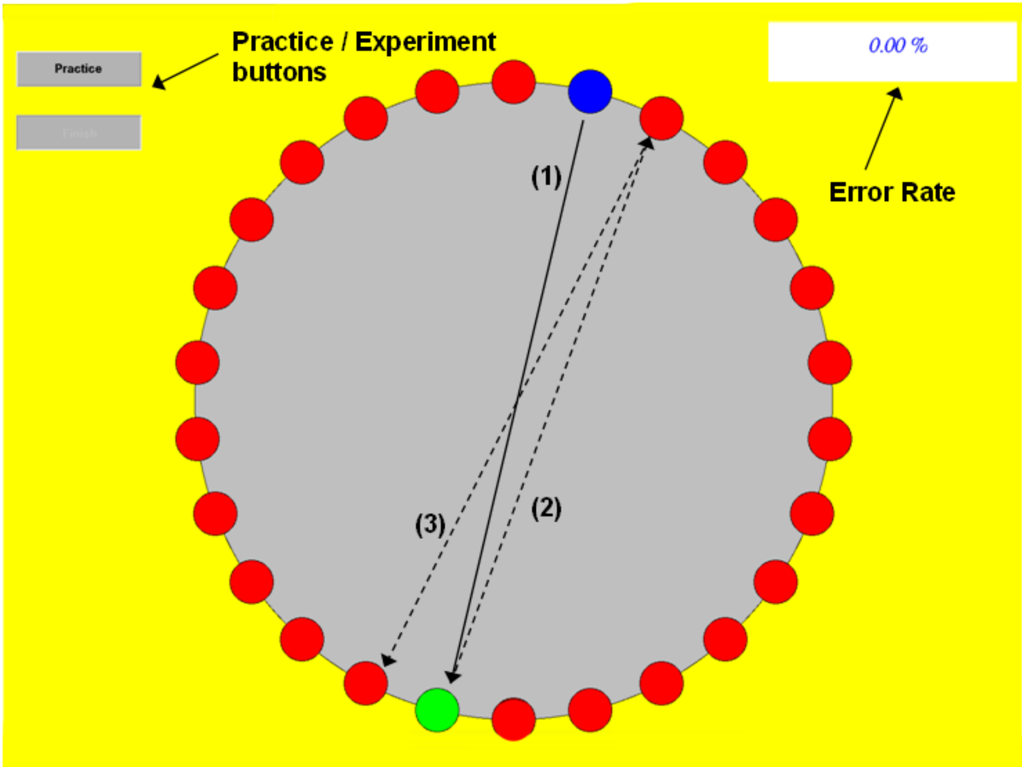


Figure 4.2: The interface for the first experiment, where participant are required to click on the illuminated (green) target. Once a target is successfully acquired, it is deactivated (i.e., turns red) and the opposite target is activated (i.e., turns green). Steps 1, 2, and 3 outline the path participants should take to acquire the first three targets. Once the first target is acquired, it turns blue, so that participants know the position of the last target.

practice tasks, to inform them that they had finished practicing and should start the experimental tasks by clicking on the Experiment button.

4.1.4 Design

The experiment was a 3×3×2 within-subjects design with repeated measures ANOVA. The factors were as follows:

- Input Device: mouse, touchpad, and Swiftpoint.
- Width of target W: 4, 8, 19, and 34 pixels.
- Distance to target D: 300 and 500 pixels.

Pointing Device	Mean Time	SD	SE
Mouse	1.24	0.37	0.04
Touchpad	2.23	0.69	0.07
Swiftpoint	1.61	0.51	0.05

Table 4.1: Mean acquisition time, standard deviation, and standard error for the three pointing devices tested during the first experiment.

These factor levels produced six different indices of difficulty (3.17, 3.91, 4.75, 5.25, 6.25, 6.98), using Fitts' formula for index of difficulty (Equation 2.11). Dependent variables were movement time MT, error rate, and throughput TP. Independent variables were W and D, determined by the width and amplitude[4] of targets. For every task, movement time was calculated by measuring the elapsed time between clicking on two opposite targets.

Fifteen participants were recruited for the experiment, however data for one of the participants was not included in experimental analysis due to a system crash, which caused an error in recording the participant's data. With 14 participants, 26 tasks per block, three devices, and six different indices of difficulties, the total number of tasks in this experiment was $14 \times 26 \times 3 \times 3 \times 2 = 6552$ tasks.

Instances where a participant spent an unexpectedly long amount of time (greater than 3 standard deviations from the mean) to select a target were considered as outliers, and consequently excluded from further analysis. Time to acquire the first target was also excluded form analysis, since participants spent time to click on the Experiment button before starting the experimental tasks.

4.2 Experimental Results

Analysis of variance ANOVA produced a grand mean of 1.70s and a standard deviation of 0.68. Of the data collected 6.2% of the touchpad's data, and 0.49% of Swiftpoint's data were outliers and hence excluded from further analysis. There were no outliers for the mouse.

The results show that participants were fastest, and more accurate using

[4] Distance to target is sometimes referred to as amplitude

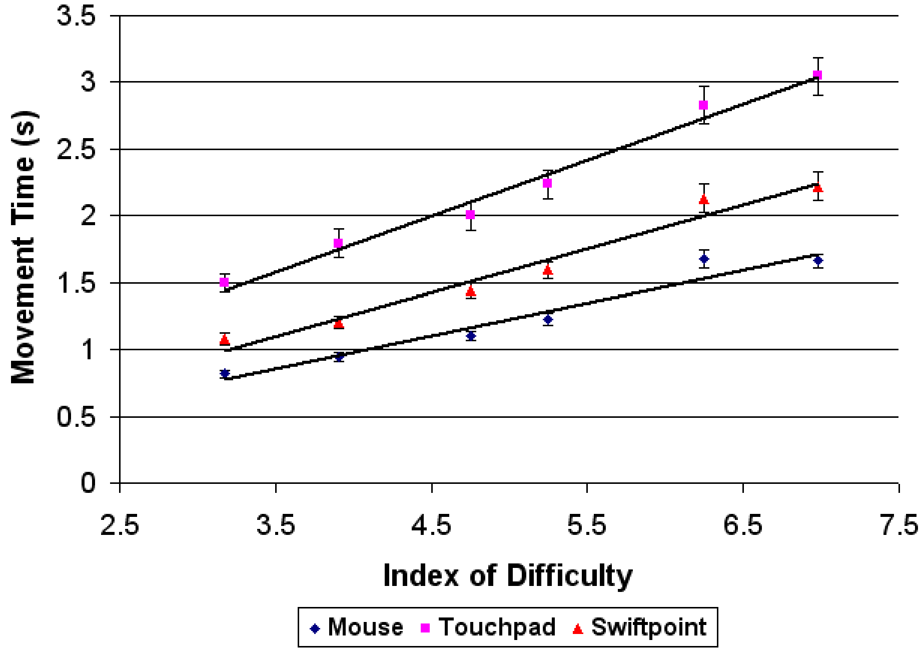


Figure 4.3: Fitts' Law results.

Pointing Device	MT	Correlation (r^2)	TP
Mouse	MT = 0.25×ID - 0.01	0.95	4.05
Touchpad	MT = 0.42×ID + 0.11	0.98	2.38
Swiftpoint	MT = 0.33×ID - 0.04	0.97	3.05

Table 4.2: Movement time equation, correlation, and throughput for the three pointing devices tested in the first experiment.

ID	Mouse	Touchpad	Swiftpoint
3.17	1.17	2.76	1.00
3.91	2.77	4.12	1.63
4.75	1.57	3.23	1.44
5.25	1.31	5.15	1.50
6.25	3.07	8.18	4.33
6.98	3.66	5.86	8.31

Table 4.3: Mean error rate for the mouse, touchpad, and Swiftpoint at different indices of difficulty.

the mouse (Table 4.1) with a mean movement time and standard deviation of (1.24s, 0.37), followed by Swiftpoint (1.61s, 0.51), and touchpad (2.23s, 0.69) giving a significant main effect for the factor pointing device, with (F (2, 26) = 74.12, $\rho < 0.001$).

There was a significant difference between the different levels of *ID* with (F (5, 65) = 317.74, $\rho < 0.001$). Significant interaction was also observed between pointing devices and indices of difficulty with (F (10, 130) = 12.123, $\rho < 0.001$).

Table 4.2 shows the line of best fit equations, correlation (r^2), and throughput *TP* for the three devices tested. All devices had an accurate correlation thus indicating a strong relationship between time and index of difficulty for the device.

The examination of the error rates for the three pointing devices (Table 4.3) showed a linear relationship between the index of difficulty and error rate (Figure 4.4), meaning that as the index of difficulty increases the error rate increases. Figure 4.4 also shows that Swiftpoint had the lowest error rate for targets with a low index of difficulty, followed closely by the mouse, and touchpad. However, as the index of difficulty increases, Swiftpoints' error rate increases to exceed that of the mouse, and the touchpad (at the highest *id*).

4.3 Discussion

In an effort to make participants adjust their speed vs. accuracy movement (i.e. be slow and accurate vs. fast and less accurate), an error rate indicator

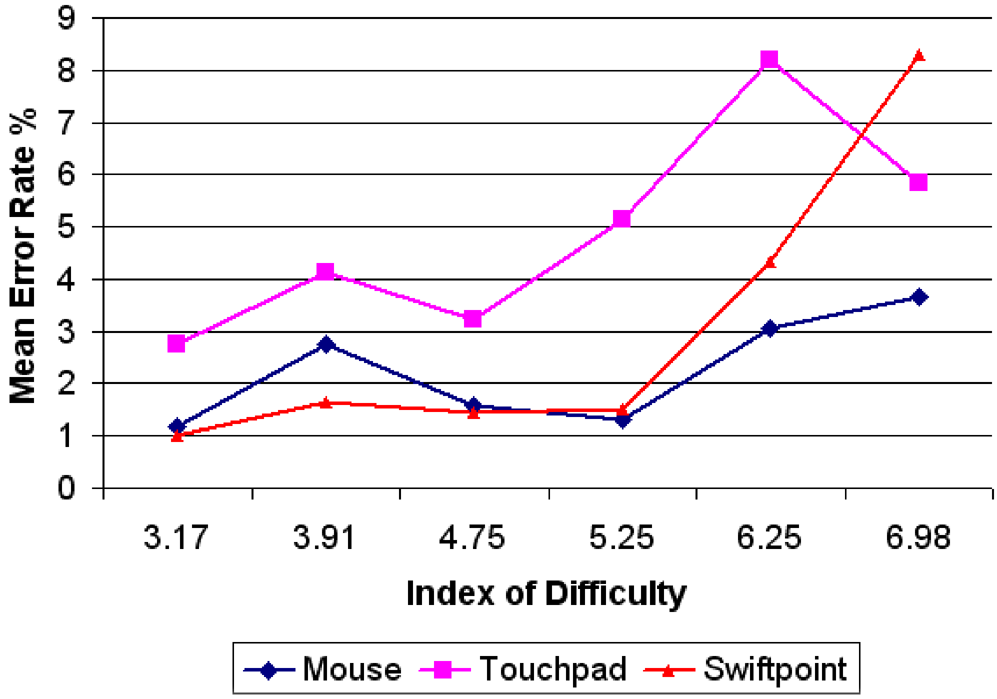


Figure 4.4: Mean Error Rate for the three pointing devices.

was displayed on the top right–hand corner of the interface. This turned red once the participant exceeded the 4% error rate recommended by ISO 9241-9 (Soukoreff & MacKenzie 2004), allowing participants to adjust their movement behaviour accordingly.

Results of the experimental evaluation showed that both the mouse and Swiftpoint were faster and more accurate than the touchpad. The mouse did also outperform Swiftpoint in terms of user preference and speed, but this may be due to two factors: (a) participants' daily use of the mouse as their primary pointing device; and (b) the use of a tablet with Swiftpoint caused clutching (i.e., participants had to lift Swiftpoint and reposition it, once Swiftpoint reaches the edges of the tablet).

Participants were more accurate with Swiftpoint than with the mouse for targets with a low index of difficulty, with an average error rate lower than the ISO 9241-9 recommended 4%. However, as the index of difficulty increased, Swiftpoint's error rate increased beyond 4% to exceed that of the mouse and touchpad. The high error rate for both the touchpad and Swiftpoint, at high indices of difficulty, could be due to participant's focus on speed rather than both speed and accuracy (i.e., completing the task as fast as possible vs. as fast and as accurately as possible) which ultimately caused more errors and hence, more time in completing the task. This trend was not observed with the mouse, due to the participant's high experience with the mouse.

Swiftpoint's intercept a was slightly lower than the minimum recommended value for a negative intercept (– 0.04s vs. – 0.02s) (Soukoreff & MacKenzie 2004). This could be due to two factors: (a) participants were observed overshooting the target before re-entring the target and selecting it, and (b) the short amount of time in which participants practiced with Swiftpoint compared to their daily use of the mouse. These factors could increase participants' dwell time[5]. Even though Swiftpoint had a lower than expected intercept, its intercept was closer to zero than that of the touchpad, thus proving the robustness of Swiftpoint's fit compared to that of the touchpad.

The high correlation ($r^2 > 0.9$) proved that Fitts' Law does apply to Swiftpoint. The lower movement time and error rate, and the higher throughput of Swiftpoint than those of the touchpad, proves that Swiftpoint is significantly better than one of the most common devices with mobile computers, the touchpad. The mouse, however did outperform Swiftpoint, thus proving its superiority over current computer pointing devices.

4.4 Conclusion

A target acquisition experiment based on the famous Fitts' Law was performed to evaluate and compare the new pointing device, Swiftpoint, to two pointing devices (mouse , and touchpad) that are commonly used with mobile computers.

Results of the experiment showed a linear relationship between index of difficulty and movement time, as well as a high correlation for Swiftpoint, thus proving the applicability of Fitts' Law to model Swiftpoint in target

[5] Dwell time is the time a user takes to move the pointer to the target before selecting it.

acquisition experiments.

Moreover, Swiftpoint was superior to the common touchpad in almost every criteria, thus proving that Swiftpoint is a suitable pointing device that is capable of doing one of the most common tasks performed by users, target selection. However, the mouse was superior to Swiftpoint, except in the error rate category, which could be explained by participant's familiarity and extensive use of the mouse as their primary pointing device.

Chapter V

Steering Law Experiment

The Steering Law applies to actions such as navigation through nested menus, dragging, drawing, and writing, most of which are performed regularly by computer users while interacting with graphical user interfaces. The primary objective of this experiment is to examine how participants would perform such interaction tasks using Swiftpoint, by applying the linear tunnel version of the Steering Law (Card et al. 1978, Douglas et al. 1999) to test the speed and accuracy of Swiftpoint against two pointing devices, Microsoft IntelliMouse and a Cirque Smart Cat touchpad. Reasons for selecting these pointing devices are discussed in Chapter 4.

Section 5.1 discusses the experimental method, including information about participants recruited for the experiment, apparatus, experimental procedure, and design. While section 5.2 presents results and analysis of the experiment. Discussion and conclusion are presented in sections 5.3 and 5.4 respectively.

5.1 Experimental Method

The same participants conducted both experiments. Information about participants, and the experimental apparatus are identical to that discussed in sections 4.1.1 and 4.1.2 respectively.

5.1.1 Procedure

The interface for this experiment was modelled after the linear-tunnel version of the Steering Law (Figure 2.15(b)). The experiment consisted of a total of seven blocks of tasks for every device, where a block consists of using the pointing device to drag the cursor (i.e., highlight) through a series of eight pieces of text located at random positions. Every task has a constant tunnel

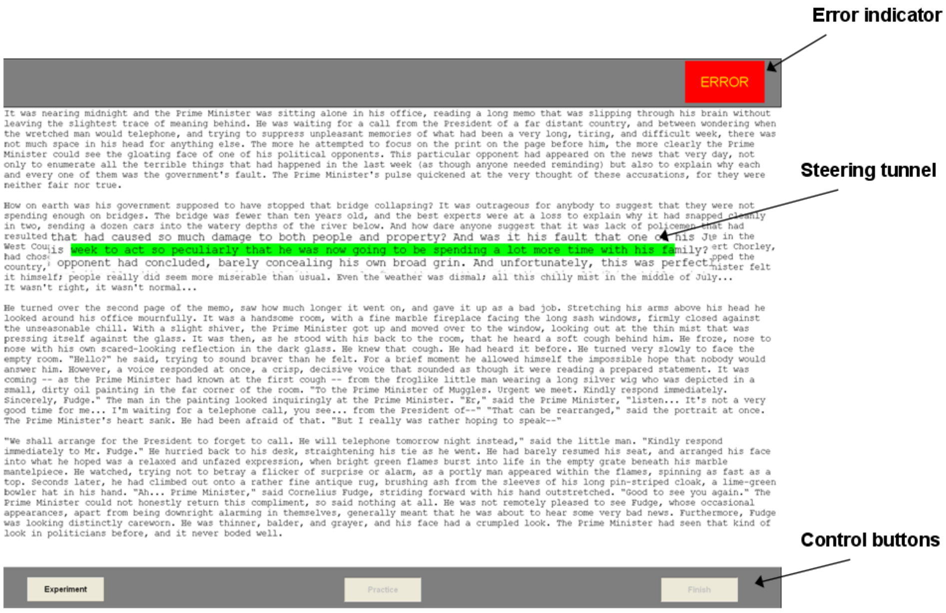


Figure 5.1: The interface for the second experiment, where participants were required to drag the cursor through the highlighted tunnel. The tunnel is represented by a green rectangle that covers a number of words, depending on the tunnel length.

width of 18 pixels, but different index of difficulty (20 – 60), as determined by the tunnel height and seven tunnel lengths (360–1080 pixels). Participants would spend around five minutes with each device and a total of 20 minutes to complete the whole experiment (including practice tasks). The experimental interface (Figure 5.1) consisted of a one page text document, three control buttons (Practice, Experiment, and Finish)[1] at the bottom of the interface, and an error indicator on the top right-hand corner. A task would require the participant to click and drag the cursor (i.e., highlight) through the illuminated (green) tunnel. Once a tunnel is highlighted and the participant releases the mouse button, the tunnel is deactivated, and another tunnel is illuminated. Participants' speed, error rate, out of path movement, index of difficulty, distance, and tunnel width, were logged for further anal-

[1] The Practice button started a series of practice tasks, while the Experiment button started experimental tasks, and the Finish button ended the experiment.

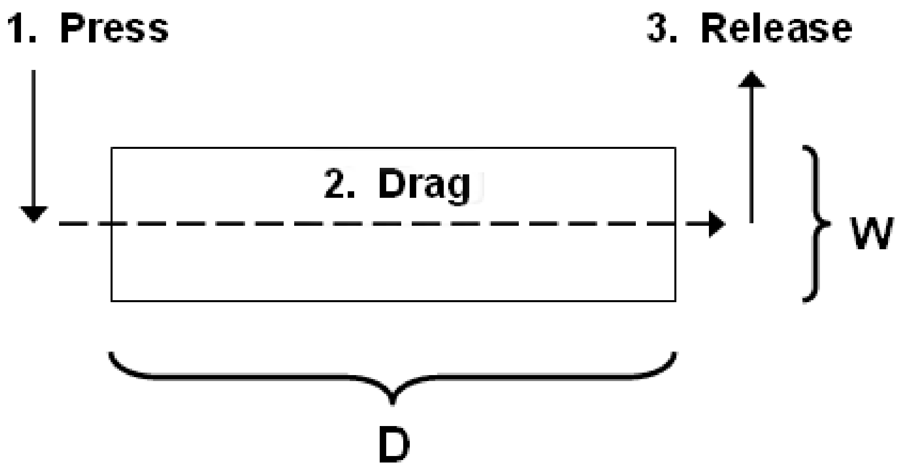


Figure 5.2: To successfully perform a task, participants were required to press the device's primary button, steer through the tunnel, and release the button.

ysis. Participants were given identical instructions to those in section 4.1.3, however due to the different nature of this experiment, they were given the following instructions:

- Press the pointing device's primary button, steer through the tunnel, and release the button (Figure 5.2).

- A double click, a click or a release at the wrong position in side the tunnel boundaries, or a release outside the horizontal tunnel boundaries, counts as an error.

- If an error is committed, a gentle sound is produced, and an error indicator on the top right corner flashes in a red colour.

- Redo the task if an error is committed.

- Stay within the tunnel boundaries, if possible. However, if you inadvertently steered outside the tunnel boundaries but complete the task successfully, a warning indicator will flash in a yellow colour, at the top right corner of the interface.

Pointing devices were exposed to each participant in random order. Similar messages to those in the first experiment, were displayed to inform participants to plug-in the appropriate pointing device, and click on the appropriate button for practice or experimental tasks. Another message indicated the end of the experiment.

After finishing both experiments, participants were asked to complete a NASA-TLX questionnaire (Appendix A) to rate their experience with Swiftpoint. Another NASA-TLX questionnaire (Appendix B) required participants to rate their experience with the three pointing devices. Results of the two questionnaires are shown in Chapter 6.

5.1.2 Design

The experiment was a 3×7 within-subjects design with repeated measures ANOVA. The factors were as follows:

- Input Device: mouse, touchpad, and Swiftpoint.
- Distance to target D: 360, 480, 600, 720, 840, 960, and 1080 pixels.

With tunnel width fixed at 18 pixels, these factors produced seven different indices of difficulties (20, 26.64, 33.36, 40, 46.64, 53.36, and 60) by using the reduced Steering Law formula for index of difficulty (Equation 2.23). Dependent variables were movement time MT, error rate, and throughput TP. The independent variable was ID, determined by the width and amplitude of targets. For every task, time was calculated by measuring the dragging time (i.e., the time the participant takes to click-drag-release) through the tunnel.

Fifteen participants conducted this experiment, with data for one participant being excluded from further analysis due to a system crash that caused a loss of some of the participant's data. The experiment had eight tasks per block, three devices, and seven different indices of difficulties, the total number of tasks in this experiment was $14 \times 8 \times 3 \times 7 = 2{,}352$ tasks.

Instances where a participant spent an unexpectedly long amount of time (greater than 3 standard deviations of the mean) to select a target were considered as outliers, and consequently excluded from further analysis.

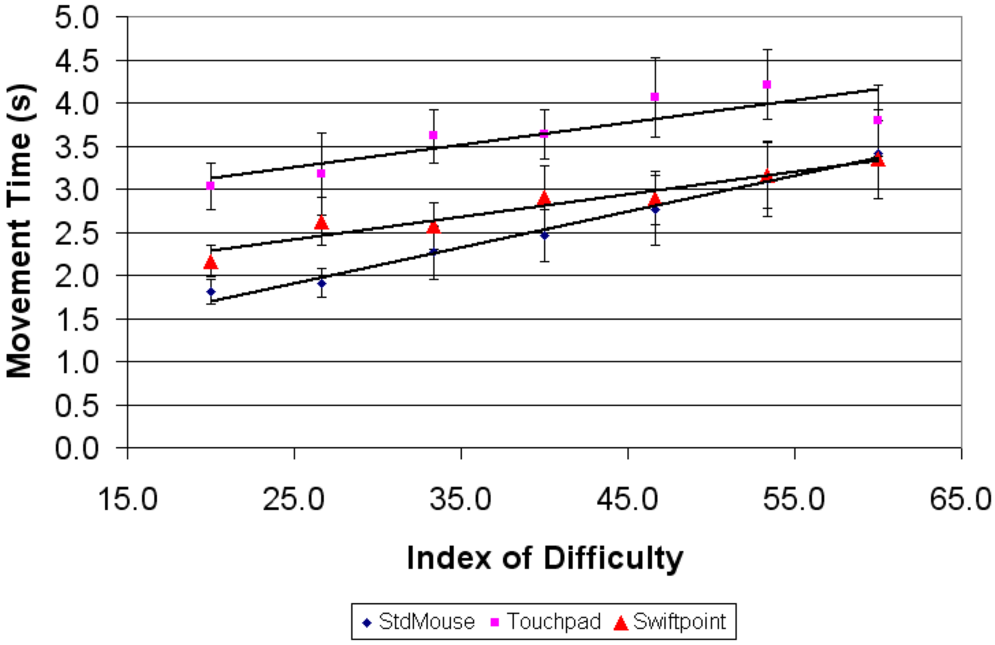


Figure 5.3: Steering Law mean movement time for the three pointing devices.

5.2 Experimental Results

Analysis of variance (ANOVA) produced a grand mean of 3.00s and a standard deviation of 1.44. Of the data collected (i.e., steering times) 7.59% of the touchpad's data, 1.38% of the Swiftpoint data, and 0.48% of the mouse data were outliers and hence excluded from further analysis.

The results show that participants were fastest using the mouse (Table 5.1) with mean movement time and standard deviation of (2.53s, 1.39), followed by Swiftpoint (2.81s, 1.25), and touchpad (3.65s, 1.44) giving a significant main effect for the factor of pointing device, with (F (2, 26) = 15.64, $\rho < 0.001$).

There was a significant difference between the different levels of *ID* (F (6, 78) = 12.58, $\rho < 0.001$). However, interaction between pointing devices and indices of difficulty was not significant (F (12, 156) = 1.11, $\rho = 0.35$). Figure 5.3 shows the mean steering time against index of difficulty (*ID*) for the three pointing devices, where the performance of both Swiftpoint and the mouse converges as the index of difficulty increases. Table 5.2 shows the

Pointing Device	Mean Time	SD	SE
Mouse	2.53	1.39	0.14
Touchpad	3.65	1.44	0.15
Swiftpoint	2.81	1.25	0.13

Table 5.1: Mean steering time, standard deviation, and standard error for the three pointing devices tested during the second experiment.

Pointing Device	MT	Correlation (R^2)	TP
Mouse	MT = 0.21×ID + 1.75	0.93	4.73
Touchpad	MT = 0.33×ID + 0.88	0.99	3.02
Swiftpoint	MT = 0.21×ID + 2.61	0.74	4.84

Table 5.2: Movement time, correlation, and throughput for the three pointing devices tested in the second experiment.

ID	Mouse	Touchpad	Swiftpoint
20.00	4.67	9.73	11.71
26.64	3.17	16.42	7.07
33.36	4.49	9.69	7.18
40.00	5.08	11.65	7.34
46.64	7.46	16.89	8.66
53.36	3.10	8.42	10.32
60.00	3.81	14.76	3.11

Table 5.3: Mean error rate for the mouse, touchpad, and Swiftpoint.

line of best fit equations, correlation (r^2), and throughput TP for the three devices. All devices had an accurate correlation thus indicating a strong relationship between time and index of difficulty for the device.

The examination of the error rates for the three pointing devices (Table 5.3) showed that the mouse had the least error rate followed by Swiftpoint and the touchpad. Figure 5.4 shows a gradual increase in the error rate for the touchpad as the index of difficulty increases. On the other hand, the error rate for Swiftpoint decreased as the index of difficulty increased.

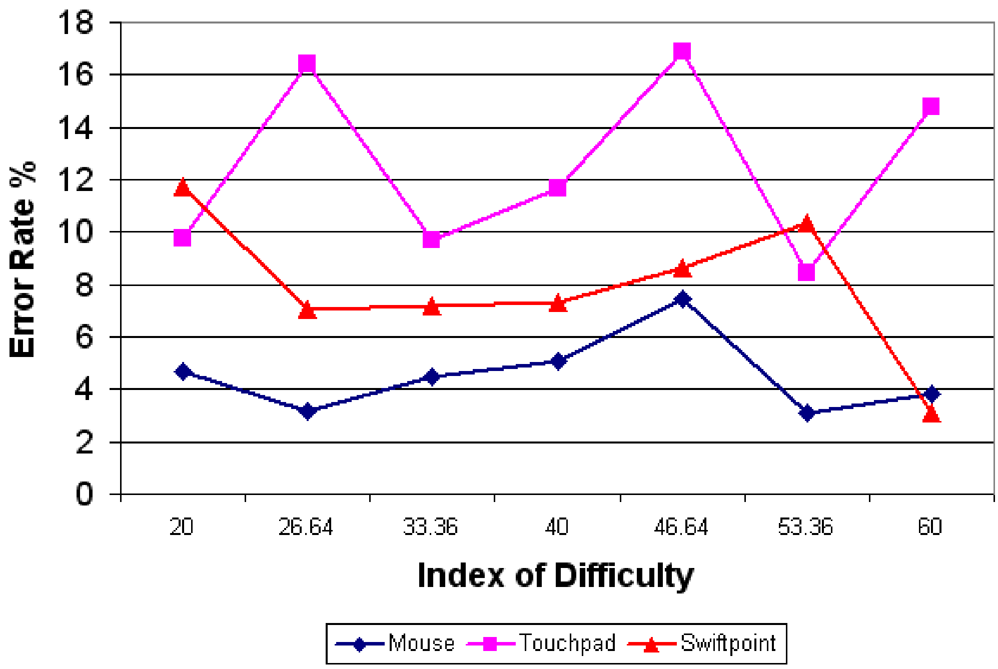


Figure 5.4: Mean Error Rate for the three pointing devices.

5.3 Discussion

This experiment showed that for all devices, the steering time increases as the index of difficulty increases. As expected, both the mouse and Swiftpoint were faster than the touchpad, with the mouse having the least mean steering time.

The touchpad had the highest correlation and least intercept among the pointing devices, followed by the mouse and Swiftpoint. However, the intercepts for the three devices were excessively high, with the touchpad having the lowest intercept followed by the mouse and Swiftpoint. This higher than usual intercept could be explained by the high frequency of out of path movement (*OPM*) committed by participants with each device.

Participants were observed steering outside the tunnel boundaries (i.e., out of path movement) to complete the task. This in some cases caused participants to finish a task faster than usual, or in other cases take longer to finish a task, as participants would try to get back in the tunnel if *OPM* occurred. *OPM* was observed in 73.86% of the tasks with the mouse, 76.02% with the touchpad, and 75.29% with Swiftpoint. Kulikov et. al experienced similiar results in their experiment, where 77% of the tasks were committed with *OPM* (Kulikov et al. 2005). Their solution was to include these data into analysis rather than execluding them as errors. Hence, the author followed Kulikov et al.'s approach in dealing with out of path movement.

Swiftpoint's performance in general was better than the touchpad, with faster steering times, higher throughput, and lower error rates. Even though the mouse was faster and had a higher correlation than Swiftpoint, it's throughput was slightly lower than that of the mouse.

Since the line of best fit shows that Swiftpoint's error rate decreases as the index of difficulty increases while the mouse's error rate stays constant, it is believed that Swiftpoint will have a lower error rate than that of the mouse for tasks with an index of difficulty greater than 60.

5.4 Conclusion

The aim of this experiment was to evaluate Swiftpoint in dragging tasks, and compare it against the mouse and touchpad. Swiftpoint had a lower steering time than the touchpad, with the mouse having the least steering time. However, as the index of difficulty increased, the steering time for both the mouse and Swiftpoint converged. A similar effect was observed with Swiftpoint's error rate. Therefore, it is expected that Swiftpoint will have a lower movement time and error rate than the mouse at higher indices of difficulty.

A moderately high correlation and a linear relationship between the index of difficulty and steering time, for the Swiftpoint, proves that the Steering Law could accurately predict Swiftpoint's steering time in constrained tunnels.

Chapter VI

Questionnaire Analysis

After finishing the experiments participants were given a Swiftpoint questionnaire (Appendix A) to evaluate their experience with Swiftpoint, and a pointing devices questionnaire (Appendix B) to compare and rate Swiftpoint performance against the mouse and touchpad. Tables 6.1 and 6.2 show the results of the two questionnaires, respectively.

Participant's preference for the pointing device of choice differed significantly (Chi-square test df $= 2$, $\chi^2 = 12.4$, $\rho < 0.01$), with 73% of participants choosing the mouse as their device of choice, and 26% choosing Swiftpoint. None of the participants indicated that they would use the touchpad. Results of the Pointing Devices questionnaire (Figure 6.1 and Table 6.2) supported the participants' preference, with the mouse having the highest mean, followed by Swiftpoint and touchpad. Friedman test showed significant difference between the Likert-scale ratings for the three pointing devices (Table 6.2).

Some of the participant's comments on the design, size, efficiency, and prolonged use of Swiftpoint were as follows:

- Design: Swiftpoint is more ergonomic than the mouse, quiet (i.e., no clicking sound), but it would be better if Swiftpoint was bigger, made out of plastic and had flat buttons. The protruding buttons are painful if Swiftpoint was used for a long priod of time.

- Size: Swiftpoint is small, compact, and easy to carry.

- Efficiency: Swiftpoint is better, and faster in clicking and dragging than the touchpad. However, it would be hard to play games using Swiftpoint.

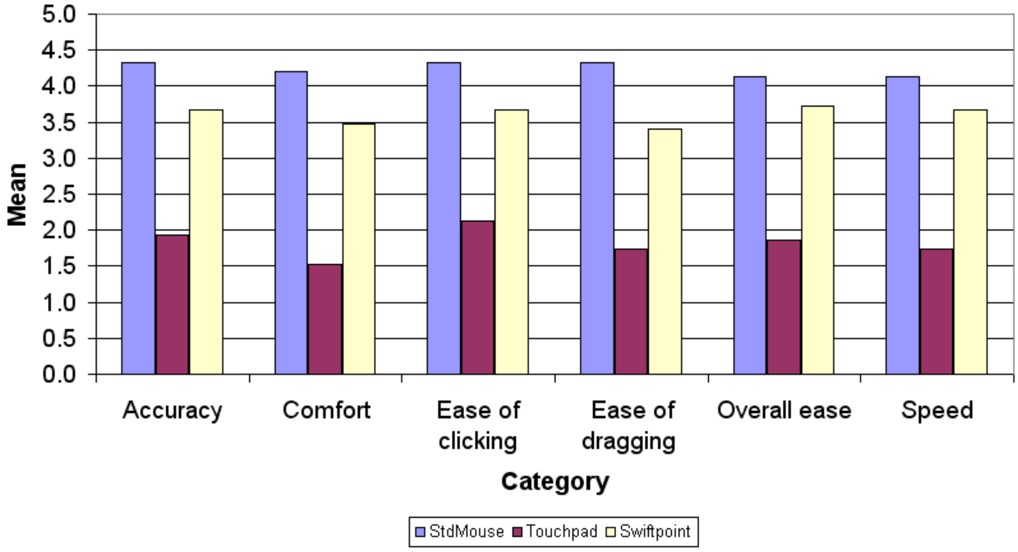


Figure 6.1: Mean results of the NASA-TLX ratings for the three pointing devices.

- Prolonged use: Swiftpoint would be better than the mouse, if used for a long period of time.

In selecting their preferred pointing device, some participants selected the mouse, and commented that their choice was based on their familiarity and experience of using the mouse. They also indicated that Swiftpoint would be easier to use than the mouse if they used it for a long period of time.

Category	Mean	SD
Force	2.80	0.68
Smoothness	3.73	1.03
Accuraccy	3.27	1.28
Mental effort	3.20	0.86
Physical effort	2.60	0.98
Frustration level	2.93	0.96
Overall performance	3.80	0.94
Operation speed	2.80	1.01
Finger fatigue	3.00	1.13
Arm fatigue	2.73	0.96
Wrist fatigue	3.27	1.16
Shoulder fatigue	3.53	1.27
Neck fatigue	3.53	1.12
General comfort	3.20	0.86
Comfort (clicking)	3.20	1.15
Comfort (dragging)	3.27	0.96
Comfort (moving pointer)	3.45	1.19
Comfort (over long period of time)	2.93	0.96

Table 6.1: Results of the Swiftpoint questionnaire.

Category	Mouse		Touchpad		Swiftpoint		Friedman Values	
	Mean	SD	Mean	SD	Mean	SD	χ_r^2	ρ
Accuracy	4.33	0.49	1.93	1.03	3.67	0.52	19.03	< 0.001
Comfort	4.20	0.68	1.53	0.99	3.47	0.83	19.03	< 0.001
Ease of clicking	4.31	0.79	2.25	1.61	3.75	1.18	11.20	< 0.005
Ease of dragging	4.33	0.90	1.73	1.35	3.40	1.18	16.23	< 0.001
Overall ease	4.13	0.83	1.87	0.91	3.73	0.88	17.73	< 0.001
Speed	4.13	0.74	1.73	0.96	3.67	0.90	18.10	< 0.001

Table 6.2: Results of the Pointing devices questionnaire showing the mean, standard deviation (SD), and results of the Friedman test analysis for the three pointing devices.

Chapter VII

Future Work and Conclusions

In this thesis I introduced the evaluation results of new pointing device, Swiftpoint, which combines the advantages of both the mouse and the stylus. An overview of the evolution of graphical user interfaces, and the subsequent reliance on pointing devices to interact with GUIs was given before introducing evaluation techniques used to test new pointing devices, and the modifications attempted before and after the release of the ISO standard on the evaluation of pointing devices.

The primary aim of this thesis was to evaluate Swiftpoint and determine if it is a suitable pointing device for pointing and dragging tasks. Three hypotheses were devised for the evaluation of Swiftpoint (Section 1.4), these were:

1. Users would select targets faster with a lower error rate using Swiftpoint;

2. Users would spend less time to steer through tunnels with Swiftpoint;

3. User would indicate their preference for Swiftpoint, in terms of speed, accuracy, and comfort, in a NASA-TLX questionnaire.

To test these hypotheses, I conducted two experiments that applied two laws: Fitts' Law and the Steering Law (Chapters 4 and 5 respectively). These two laws are recommended by the ISO 9241-9 standard in evaluating pointing devices, to predict participants' movement time in target acquisition and steering based tasks.

The two experiments conducted partially validate the above hypotheses. In Fitts' experiment, participant's speed and accuracy were tested in target acquisition tasks. Participants completed the tasks significantly faster with less error rate with Swiftpoint than with the touchpad. The mouse, on the other hand, had the highest throughput and least acquisition time than both Swiftpoint and touchpad. However, the mouse did have a higher error rate than Swiftpoint for targets with a low index of difficulty.

The Steering experiment exhibited similar results, with the mouse having the least steering time and error rate, followed by Swiftpoint and the touchpad. However, three trends were observed: first, the steering time for the mouse and Swiftpoint converges as the index of difficulty increases. Second, Swiftpoint's error rate decreases as the index of difficulty increases. These two trends indicate that for higher indices of difficulty, participants would perform tasks faster with less error rate with Swiftpoint than the mouse. Three, Swiftpoint had the least correlation, the highest throughput and intercept. This was due to the large amount of out of path movement (OPM) committed by participants, hence OPM was not considered as an error even though participants stepped outside the boundaries of the tunnel.

Overall performance of Swiftpoint was second to the mouse in target acquisition tasks, where the mouse had the highest throughput. While in dragging tasks, Swiftpoint had the highest throughput.

Swiftpoint's design was new to participants, the design is different from any available pointing device in the market. This was reflected by the progress of one participant's comments as he was conducting the experiment *"weird, not bad, as good as the mouse"*.

The ubiquity of the mouse, with computers, had an effect on participants choice for their preferred pointing device as several participants indicated that their choice was based on their familiarity with the mouse. Participants also expressed their preference for a bigger device with flat buttons. However, Swiftpoint's design was aimed at users in constrained space, where the use of a mouse would be inconvenient and the touchpad would be prone to error, as one participant commented *"the touchpad is terrible to use"*. Material and button design, on the other hand, were changed due to participants comments, the new design (Figure 3.10) is made out of plastic, and has flat buttons, such that users do not experience any discomfort while clicking on the button.

Swiftpoint proved superior to one of the most common pointing devices with laptop computers, one that is now a standard release with every laptop sold in the market; that is the touchpad. The mouse, however, did outperform Swiftpoint, but this is probably due to the participant's regular use of the mouse as their primary pointing device. Thus any new pointing device would have to significantly outperform the mouse, which is highly unlikely (Balakrishnan et al. 1997), unless it offers new features that are not available in the mouse.

Swiftpoint does have several advantages over the mouse and touchpad, such as its compact design, digital ink mode, and ergonomic design, as discussed in Sections 3.1 and 3.3. This is reflected in the experimental evaluations and subsequent questionnaires, where Swiftpoint outperformed the touchpad. Participants' choice for their preferred pointing device supported the experimental results, with the mouse as the fastest, more accurate, and preferred pointing device, followed by Swiftpoint, and touchpad. However, none of the participants chose the touchpad as their preferred pointing device.

In conclusion, results from the experiments and the subsequent questionnaires successfully evaluated the usability of Swiftpoint and provided a great and early insight into its suitability as a computer pointing device. Results showed that Swiftpoint is a promising new pointing device that outperformed the touchpad, and the mouse in some aspects, ergonomic, and suitable for pointing and dragging tasks, which boosted Swiftpoint's marketing campaign. Results also revealed few design defects that were modified accordingly. It is expected that, after the new modifications to the design of Swiftpoint, future studies would find participants perform tasks faster and more accurately, and would prefer to use Swiftpoint as their primary pointing device with mobile computers.

7.1 Future Work

Swiftpoint is currently being marketed in Japan. If successful, Swiftpoint is expected to be popular with mobile computer users. The experimental evaluation of Swiftpoint was conducted with the standard model (Figure 3.3), which was criticised by some participants. It would be valuable to evaluate the new model (Figure 3.10) against the mouse, specially after users' comments were taken into account in improving the design of Swiftpoint. Currently Swiftpoint requires a tablet to capture its movement, future models are expected to use laser technology to more accurately track its movement.

An experiment that uses a laptop with a tablet underneath to tests the use of Swiftpoint on the keyboard against that of the mouse, would produce more accurate results in testing Swiftpoint in the environment it is designed for. Another experiment could test Swiftpoint's digital ink mode against the Stylus, in writing, dragging, and selecting targets, on a tablet PC. A deployment study would prove fruitful in gathering users' reaction after using Swiftpoint for a long period of time, typically two or more weeks.

Research into Fitts' Law and Steering Law is ongoing, for example a study by Pastel (2006) produced a modification to the Steering Law such that it applies to paths with corners. Evaluating Swiftpoints in different movement conditions, such as circular and cornered paths, and drawing, would produce valuable results and insights into the capabilities of Swiftpoint as a new pointing device.

Appendix A

Swiftpoint Questionnaire

This NASA-TLX questionnaire was based on the ISO 9241-9 recommendations (Douglas et al. 1999, ISO 2000). Participants were asked to circle the number that is more appropriate to the given comment about the new pointing device (Swiftpoint).

Category	too low				too high
The force required to perform an action was	1	2	3	4	5
Smoothness during operation was	1	2	3	4	5
The mental effort required for operation	1	2	3	4	5
The Physical effort required for operation	1	2	3	4	5
The Frustration level while using Swiftpoint	1	2	3	4	5
Accurate pointing was	1	2	3	4	5
Operation speed was	1	2	3	4	5
Finger fatigue	1	2	3	4	5
Arm fatigue	1	2	3	4	5
Wrist Fatigue	1	2	3	4	5
Shoulder Fatigue	1	2	3	4	5
Neck Fatigue	1	2	3	4	5
General comfort	1	2	3	4	5
Overall ease	1	2	3	4	5
Category	very comfortable				very un-comfortable
How comfortable is the clicking action of Swiftpoint?	1	2	3	4	5
How comfortable is the dragging action of Swiftpoint?	1	2	3	4	5
How comfortable was moving the pointer?	1	2	3	4	5
How comfortable would it be to use over long periods of time?	1	2	3	4	5
Comments on Swiftpoints' design:					
Further comments on the Swiftpoint:					

Table A.1: The Swiftpoint questionnaire.

Appendix B

Pointing Devices Questionnaire

This NASA-TLX questionnaire was based on the ISO 9241-9 recommendations (Douglas et al. 1999, ISO 2000). Participants were asked to circle the number that is more appropriate to the given comment about the new pointing device (Swiftpoint).

The pointing device was accurate?	Disagree				Agree
Mouse	1	2	3	4	5
Touchpad	1	2	3	4	5
Swiftpoint	1	2	3	4	5
The pointing device was fast?	Disagree				Agree
Mouse	1	2	3	4	5
Touchpad	1	2	3	4	5
Swiftpoint	1	2	3	4	5
The pointing device was comfortable?	Disagree				Agree
Mouse	1	2	3	4	5
Touchpad	1	2	3	4	5
Swiftpoint	1	2	3	4	5
It was easy to (click on targets) with the pointing device?	Disagree				Agree
Mouse	1	2	3	4	5
Touchpad	1	2	3	4	5
Swiftpoint	1	2	3	4	5
It was easy to (highlight targets) with the pointing device?	Disagree				Agree
Mouse	1	2	3	4	5
Touchpad	1	2	3	4	5
Swiftpoint	1	2	3	4	5
Overall, the pointing device was easy to use?	Disagree				Agree
Mouse	1	2	3	4	5
Touchpad	1	2	3	4	5
Swiftpoint	1	2	3	4	5
The pointing device was	Very bad				Very good
Mouse	1	2	3	4	5
Touchpad	1	2	3	4	5
Swiftpoint	1	2	3	4	5
Please select your preferred pointing device	Mouse		Touchpad		Swiftpoint
Briefly, state the reasons for your choice.					

Table B.1: The Pointing Devices questionnaire.

Appendix C

Consent Form

I (Taher Amer from the Computer Science department) am carrying out an evaluation of a new pointing device called Swiftpoint in comparison to two other pointing devices: the mouse, and touchpad.

The experiment consists of two parts; part one consists of six blocks of short tasks that involve clicking on illuminated targets. Your total participation for this part should take approximately 20 minutes. Part two consists of seven blocks of short task that involve highlighting pieces of text. Your total participation for this part should take approximately 20 minutes.

This is not in any way a test of your competence with computers. All references to participants in the investigation will be anonymous. Thank you for your co-operation. If you have any questions about this investigation, please contact Taher: tea14@student.canterbury.ac.nz

I consent to act as a participant in an experiment that will evaluate a new pointing device "Swiftpoint" against three other pointing devices (mouse, and touchpad). I agree to let the resulting data be used for further analysis and presentation subject to the conditions below:

- only Taher will know the identity of test users and their data, and data presented or published will be stripped of my identity;

- I retain the right to stop my role as a test user at any time without question, and to have my data discarded.

Name:
Signature:
Date:

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